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Lin et al.

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(54) **METASURFACES WITH ASYMETRIC GRATINGS FOR REDIRECTING LIGHT AND METHODS FOR FABRICATING**

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G02B 5/30 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC **G02B 27/0172** (2013.01); **G02B 5/30** (2013.01); **G02B 30/35** (2020.01); **H04N 13/344** (2018.05);
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CPC G02B 27/0172; G02B 5/30; G02B 30/35; G02B 2005/1804; G02B 2027/0109;
(Continued)

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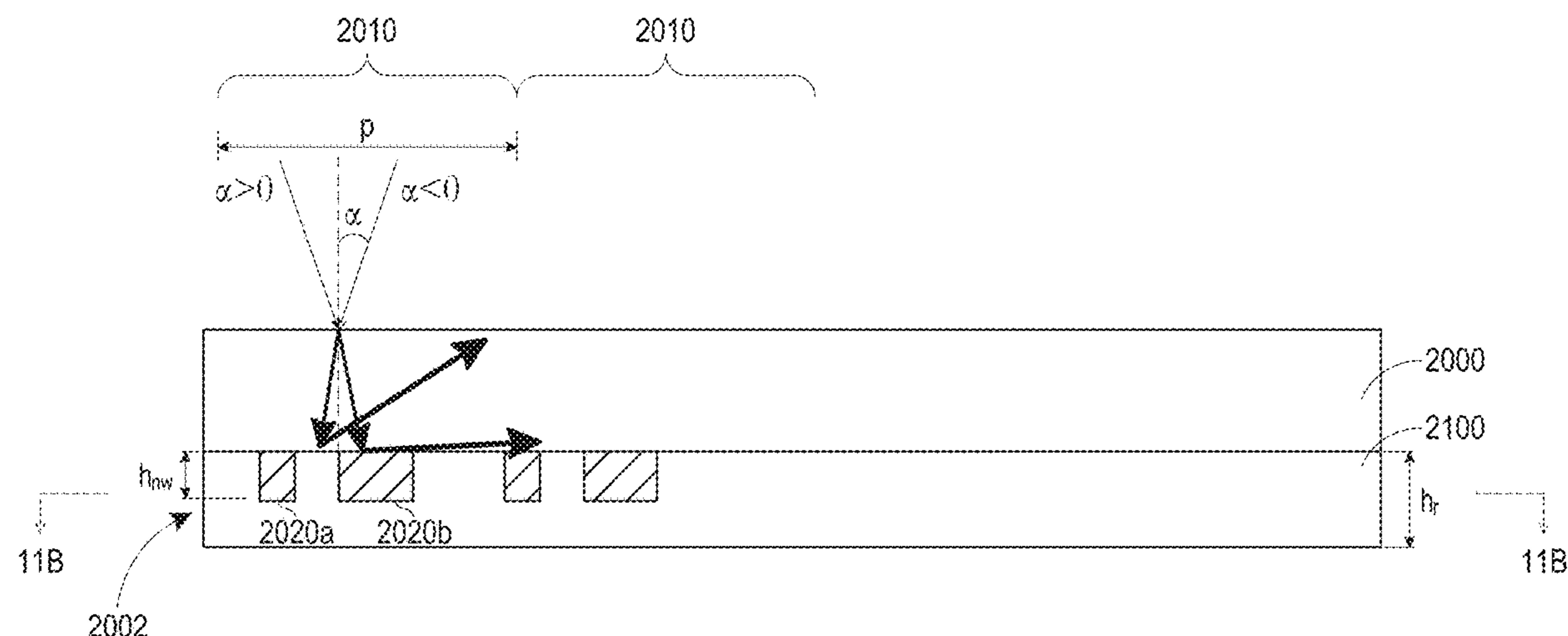
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(57) **ABSTRACT**

An optical system comprises an optically transmissive substrate comprising a metasurface which comprises a grating comprising a plurality of unit cells. Each unit cell comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width. A pitch of the unit cells is 10 nm to 1 μ m. The heights of the first and the second nanobeams are: 10 nm to 450 nm where a refractive index of the substrate is more than 3.3; and 10 nm to 1 μ m where the refractive index is 3.3 or less.

20 Claims, 27 Drawing Sheets



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	division of application No. 15/588,350, filed on May 5, 2017, now Pat. No. 10,527,851.		
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(51)	Int. Cl.		
	<i>H04N 13/344</i> (2018.01)		
	<i>H04N 13/349</i> (2018.01)		
	<i>G02B 30/35</i> (2020.01)		
	<i>G02B 5/18</i> (2006.01)		
(52)	U.S. Cl.		
	CPC ... <i>H04N 13/349</i> (2018.05); <i>G02B 2005/1804</i> (2013.01); <i>G02B 2027/0109</i> (2013.01); <i>G02B 2027/0125</i> (2013.01); <i>G02B 2027/0174</i> (2013.01)		
(58)	Field of Classification Search		
	CPC <i>G02B 2027/0125</i> ; <i>G02B 2027/0174</i> ; <i>G02B 5/1809</i> ; <i>G02B 5/3058</i> ; <i>G02B 6/34</i> ; <i>G02B 1/002</i> ; <i>G02B 27/01</i> ; <i>G02B 27/00</i> ; <i>G02B 1/00</i> ; <i>H04N 13/344</i> ; <i>H04N 13/349</i>		
	See application file for complete search history.		
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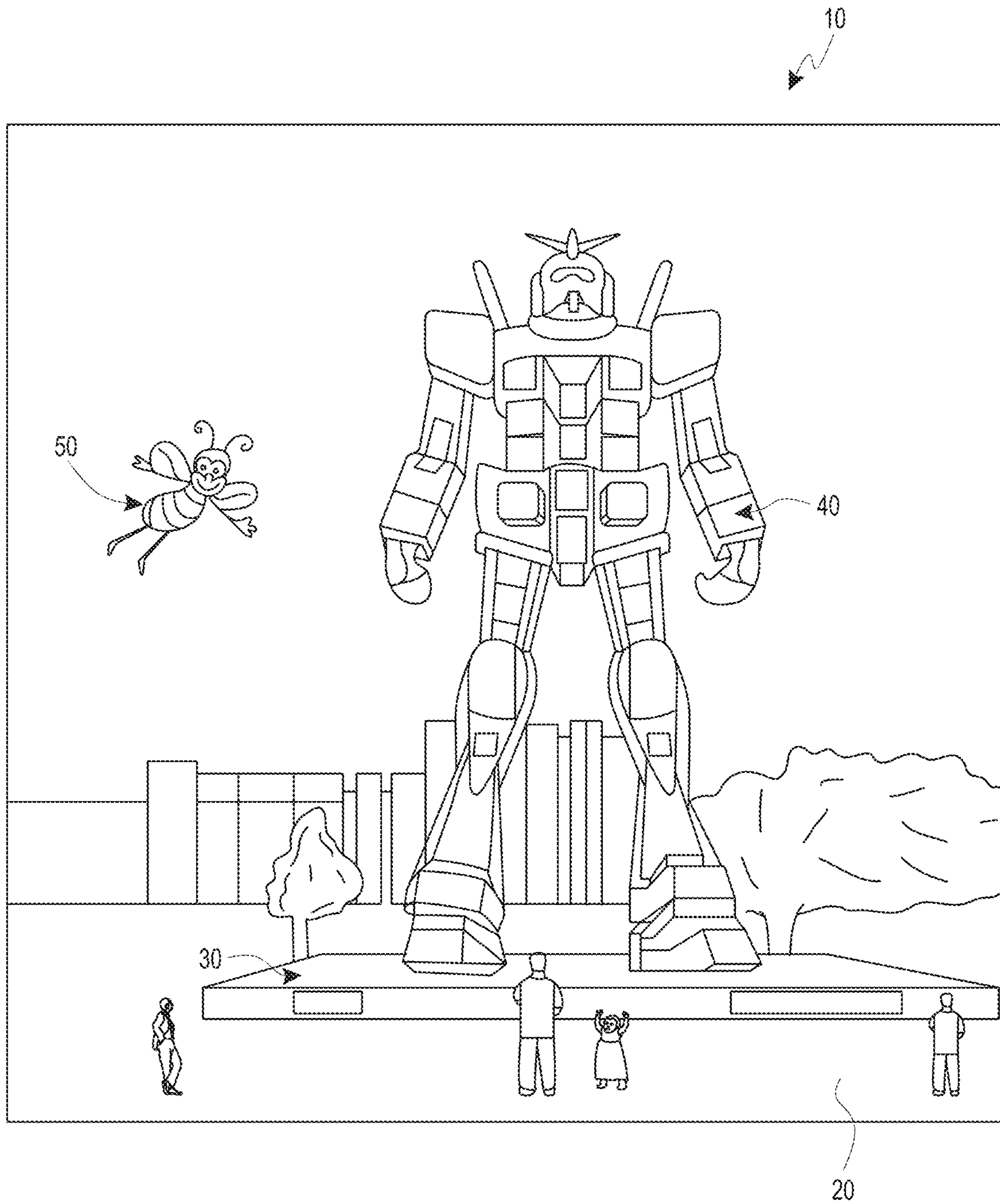


FIG. 1

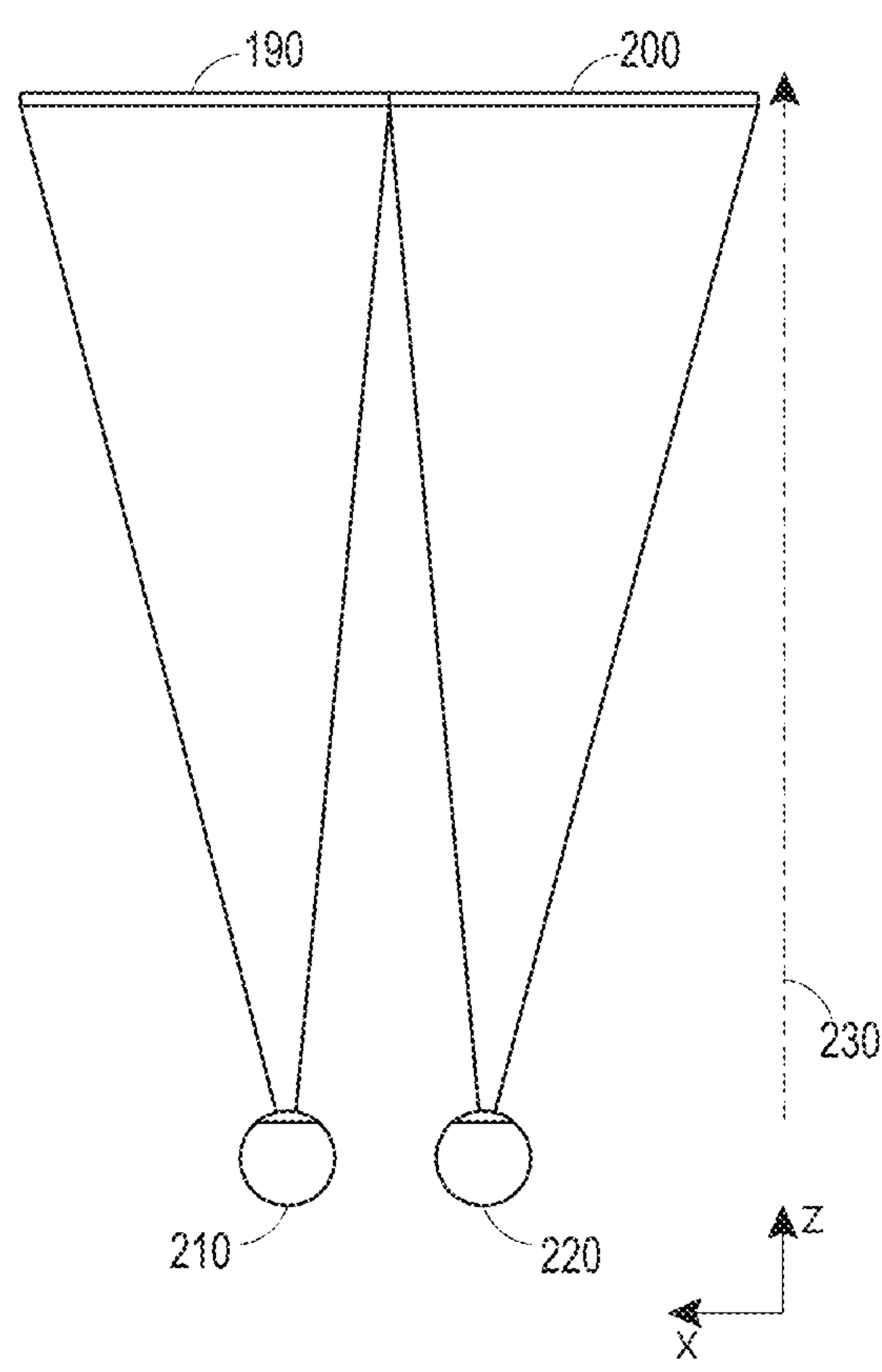
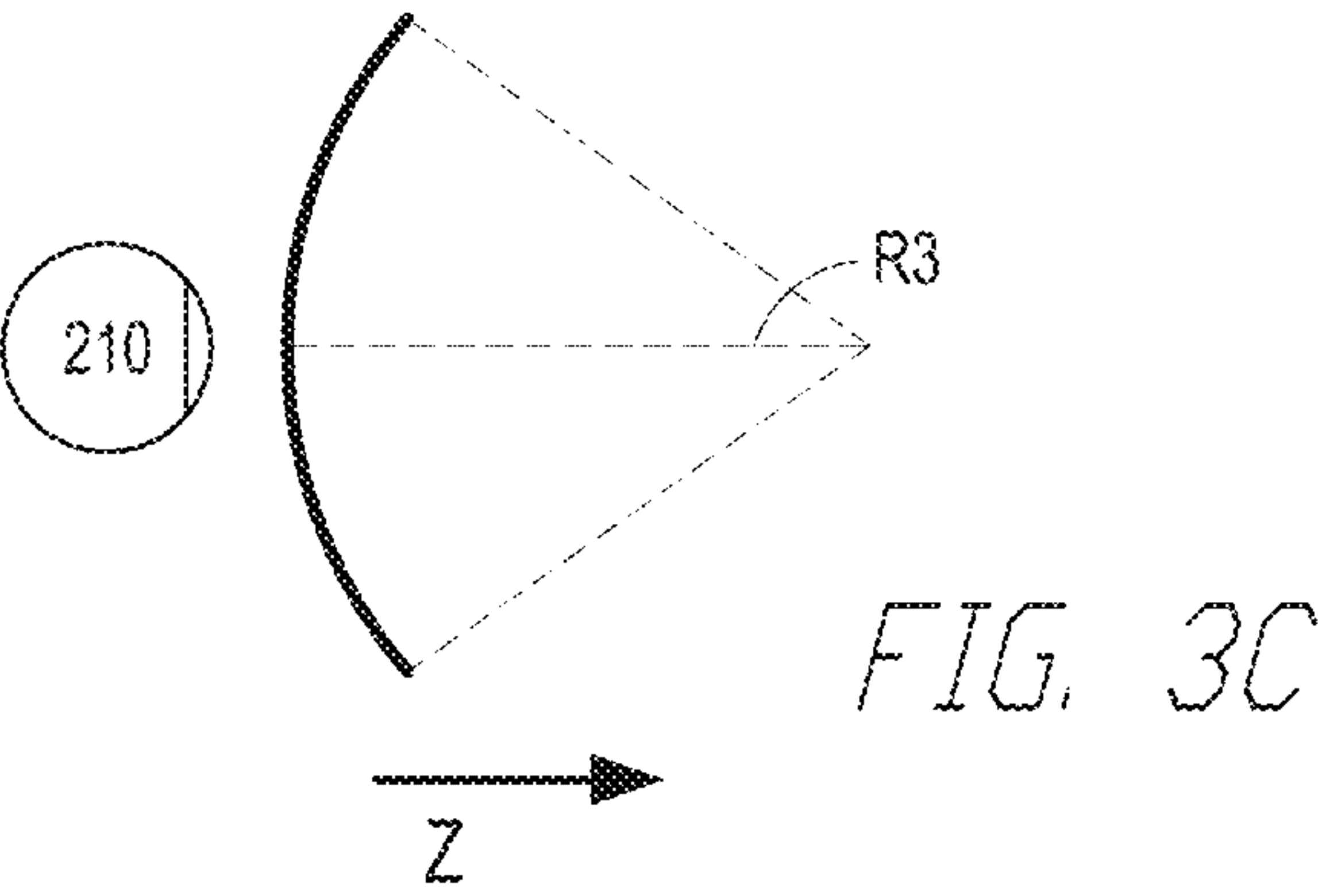
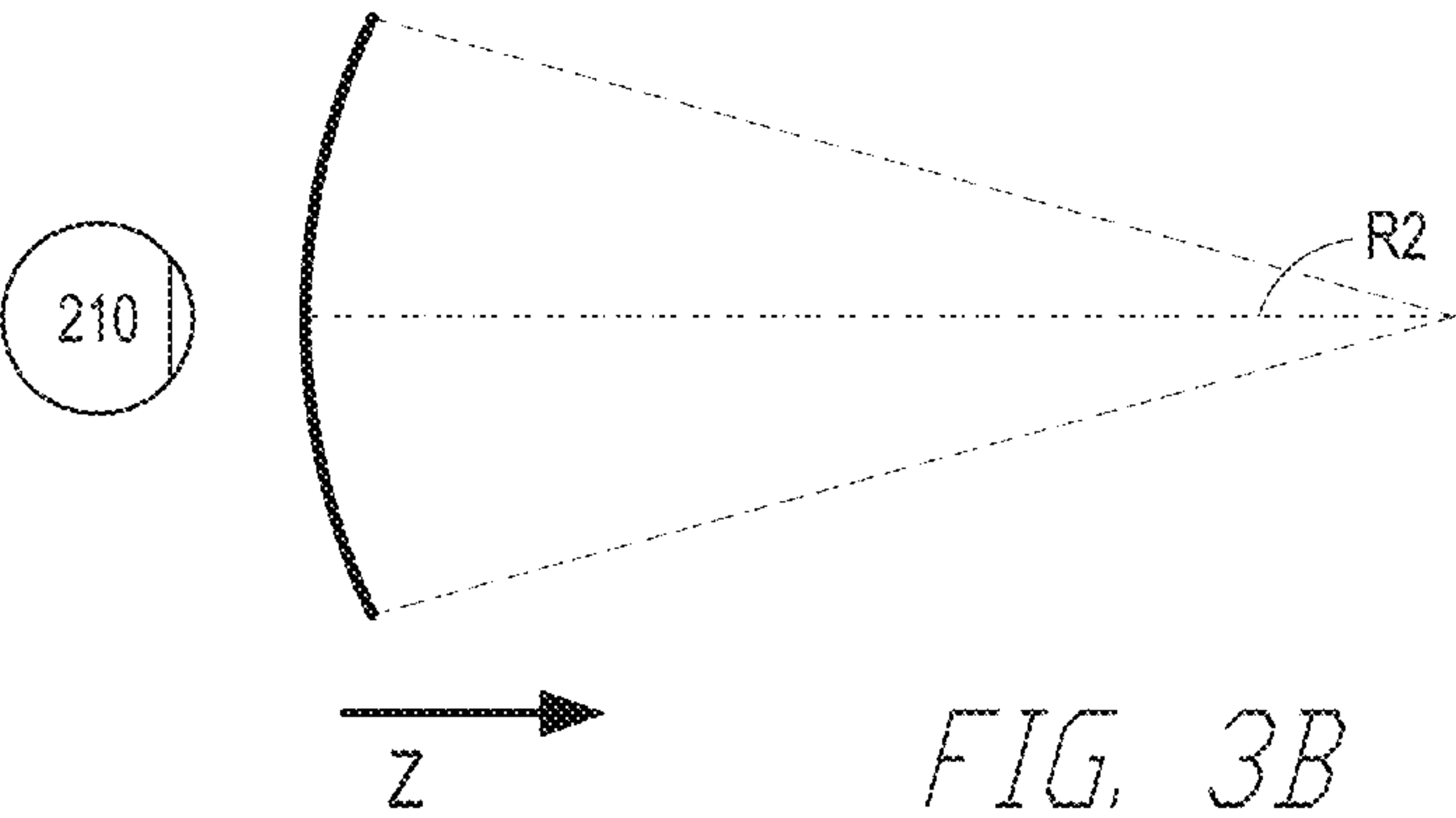
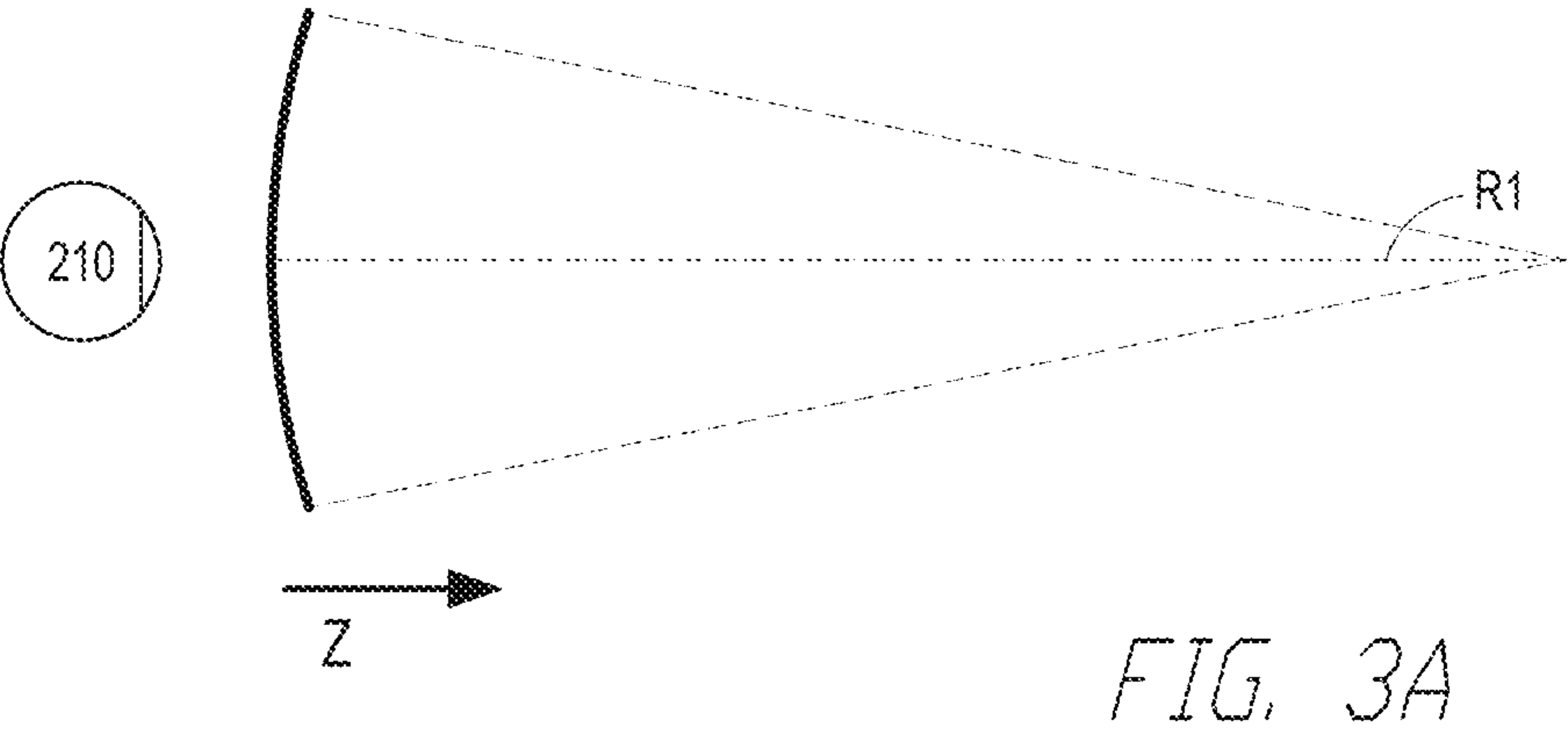


FIG. 2



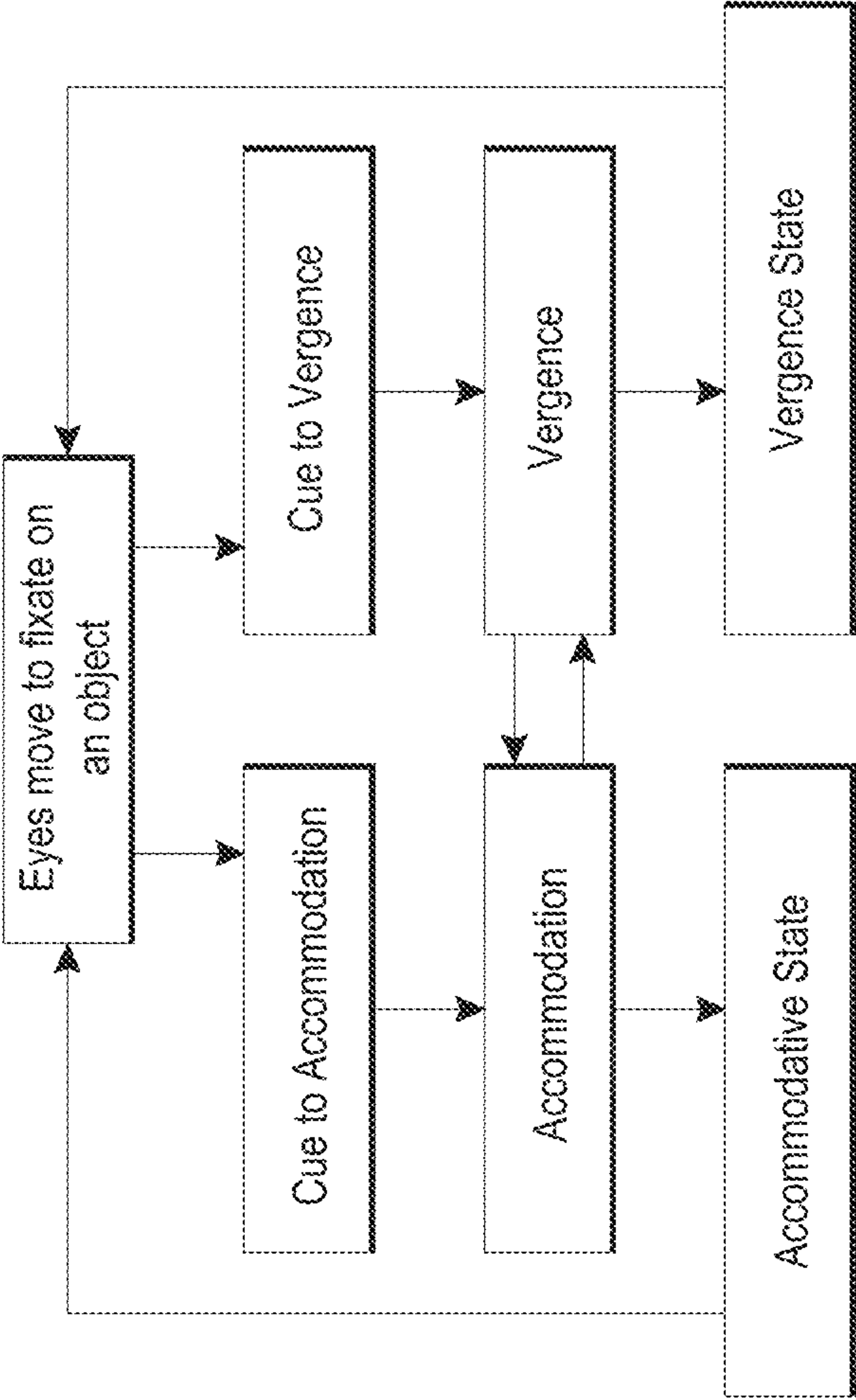


FIG. 4A

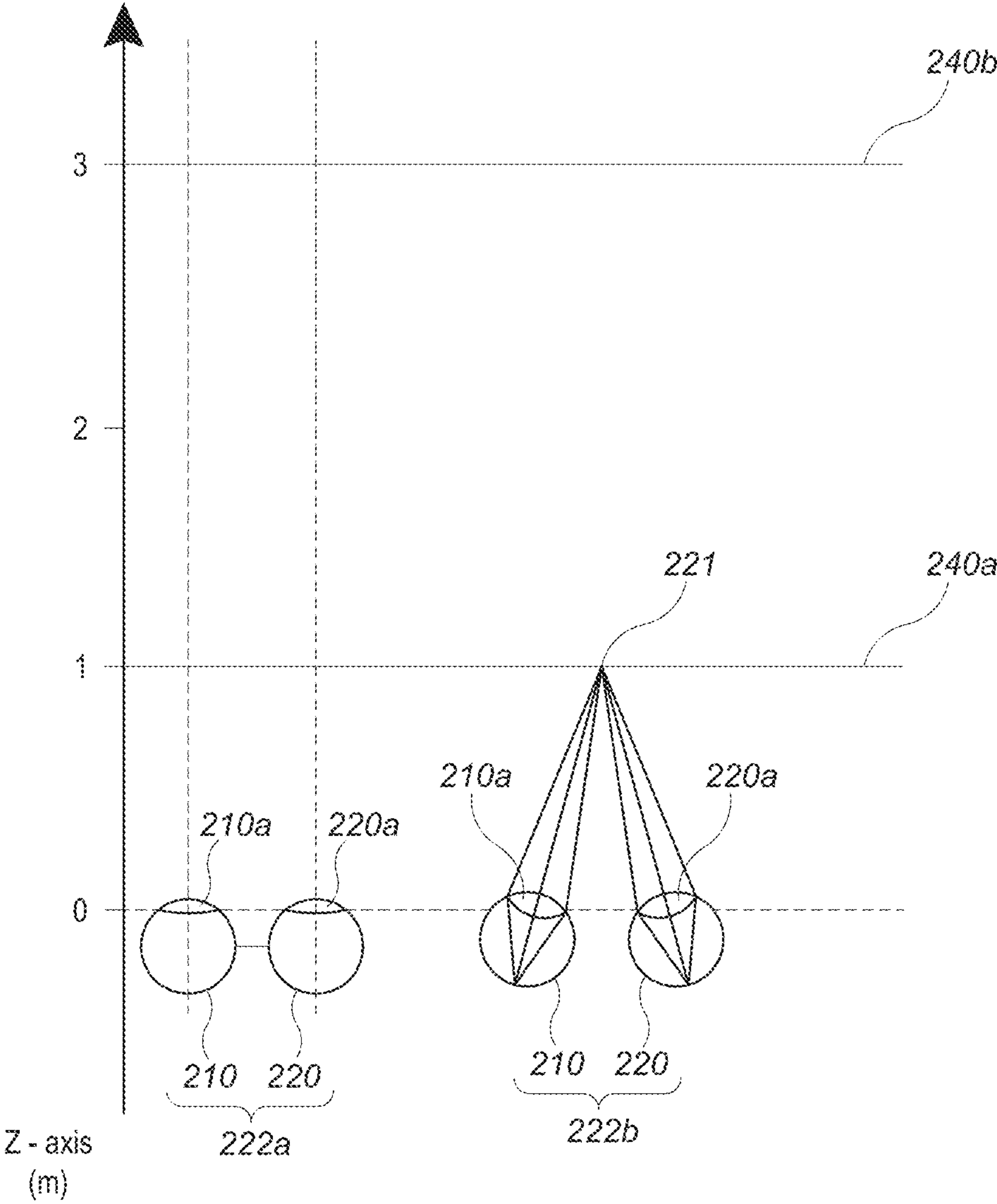


FIG. 4B

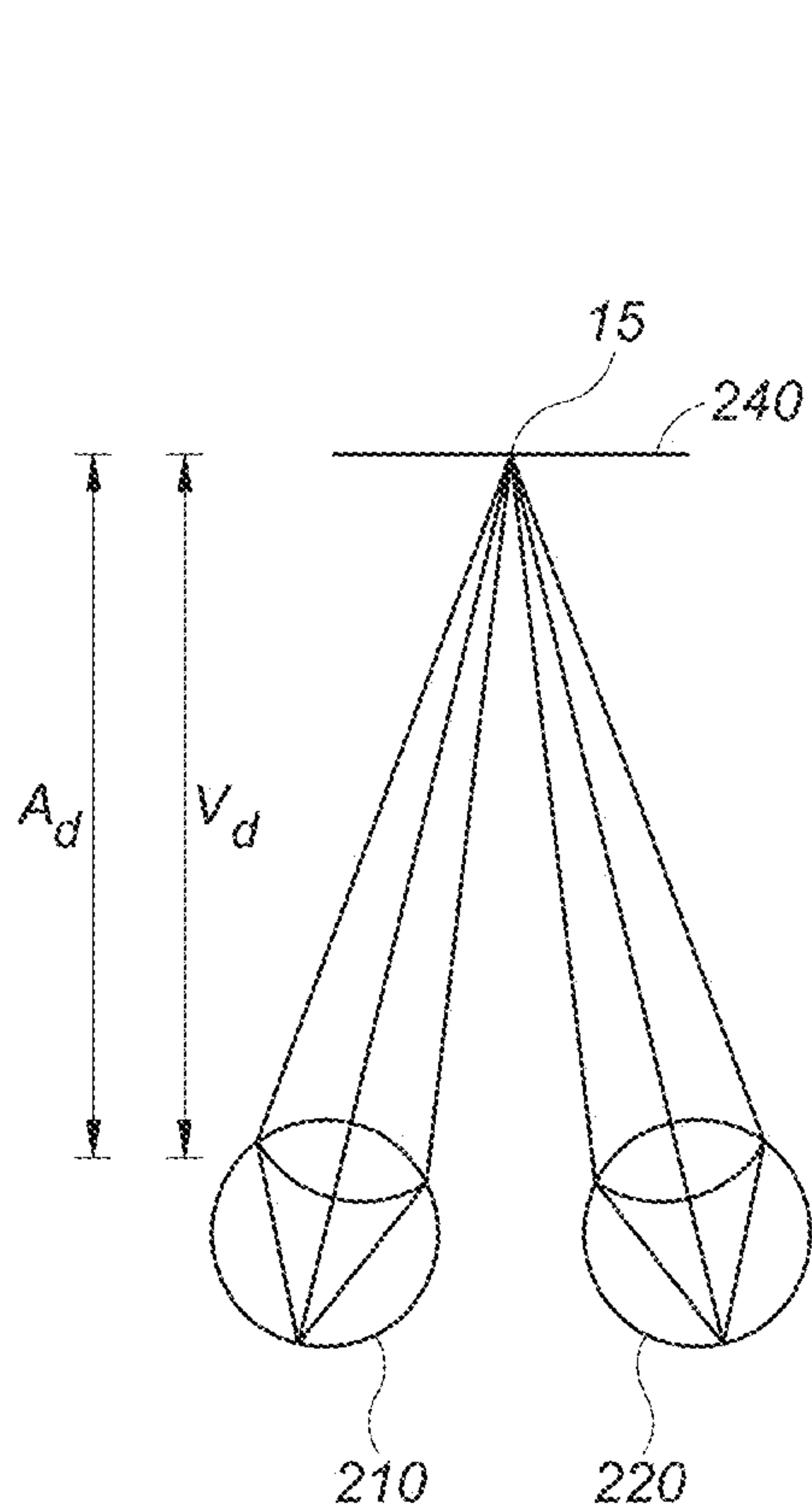


FIG. 4C

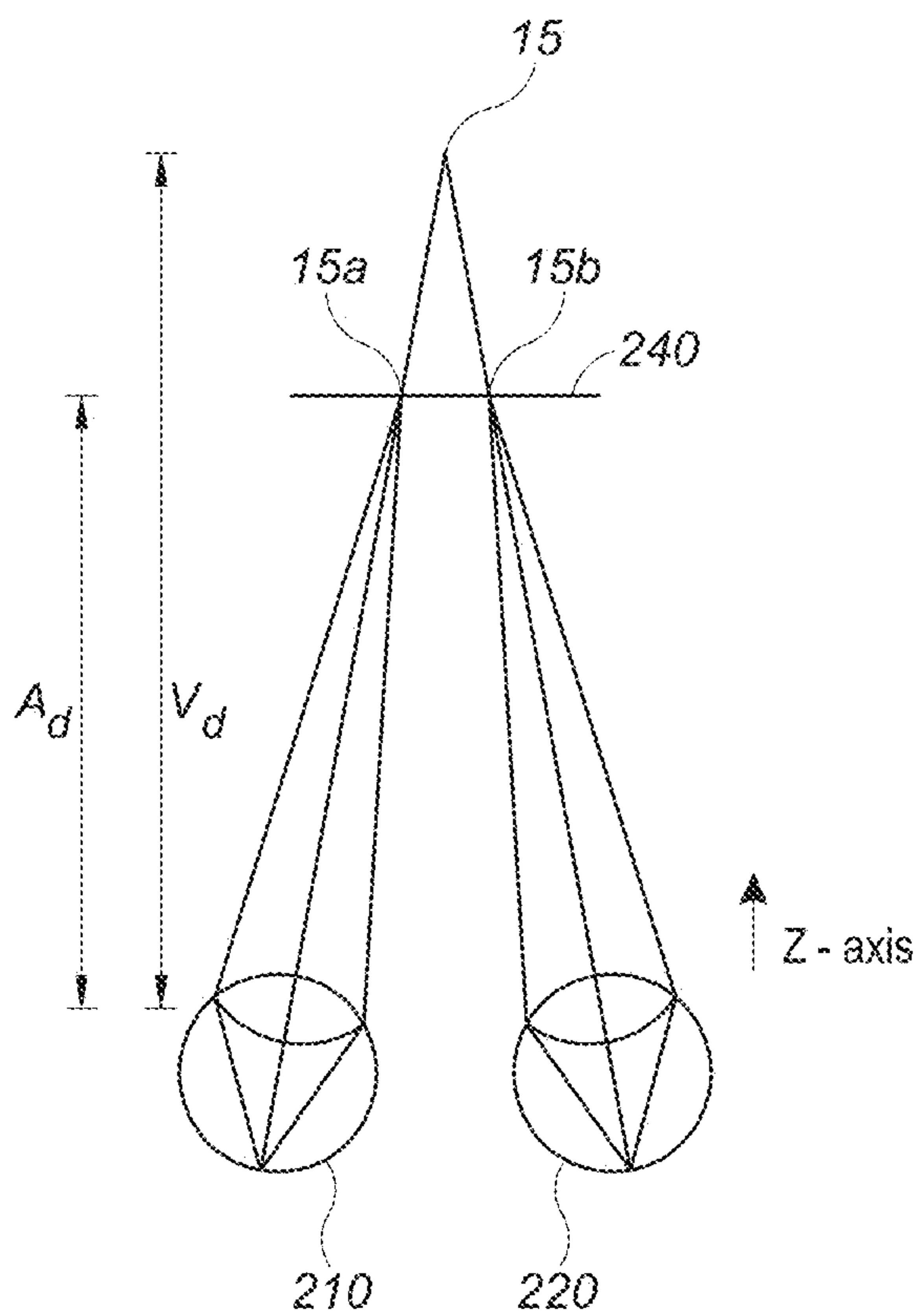


FIG. 4D

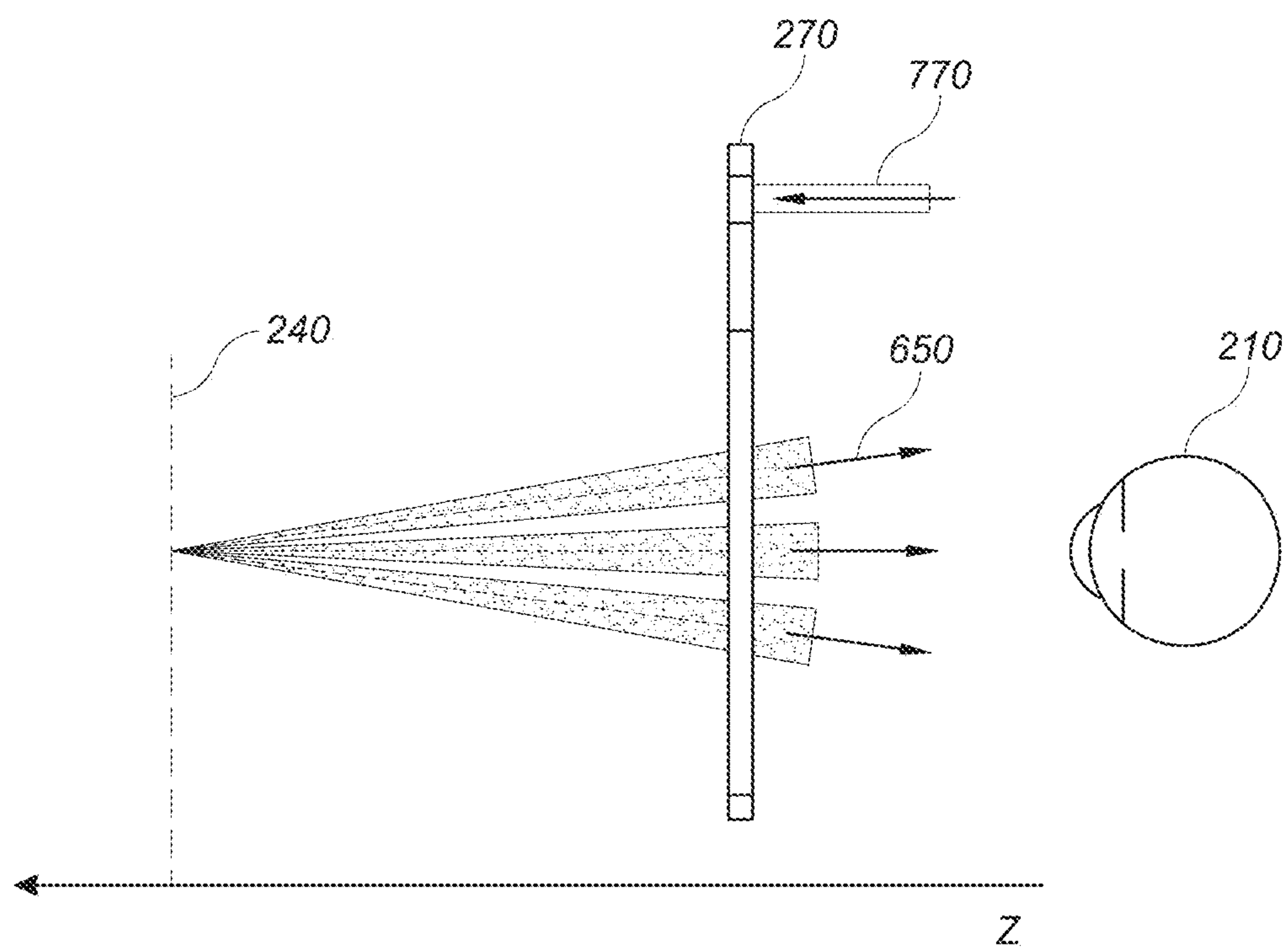


FIG. 5

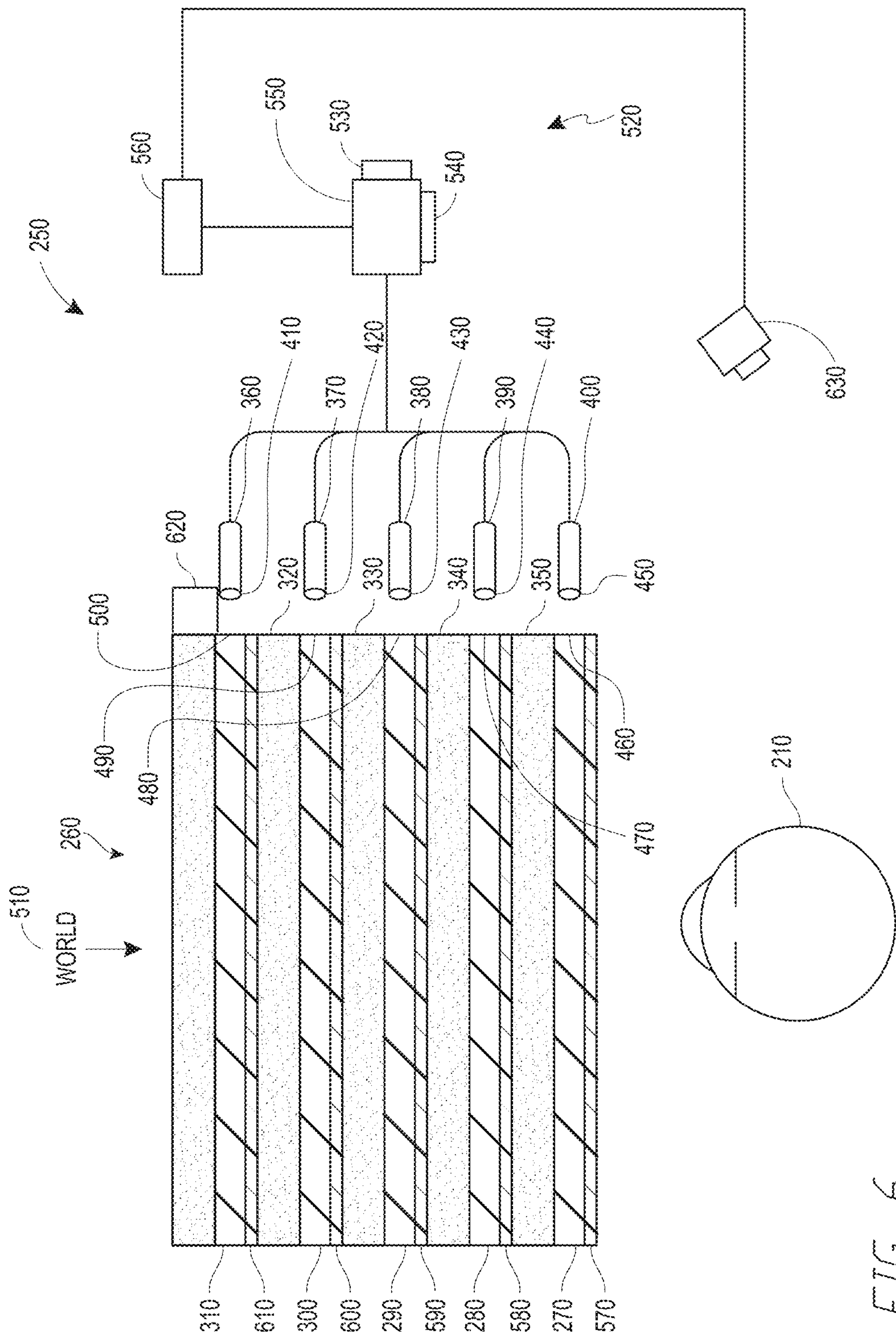


FIG. 6

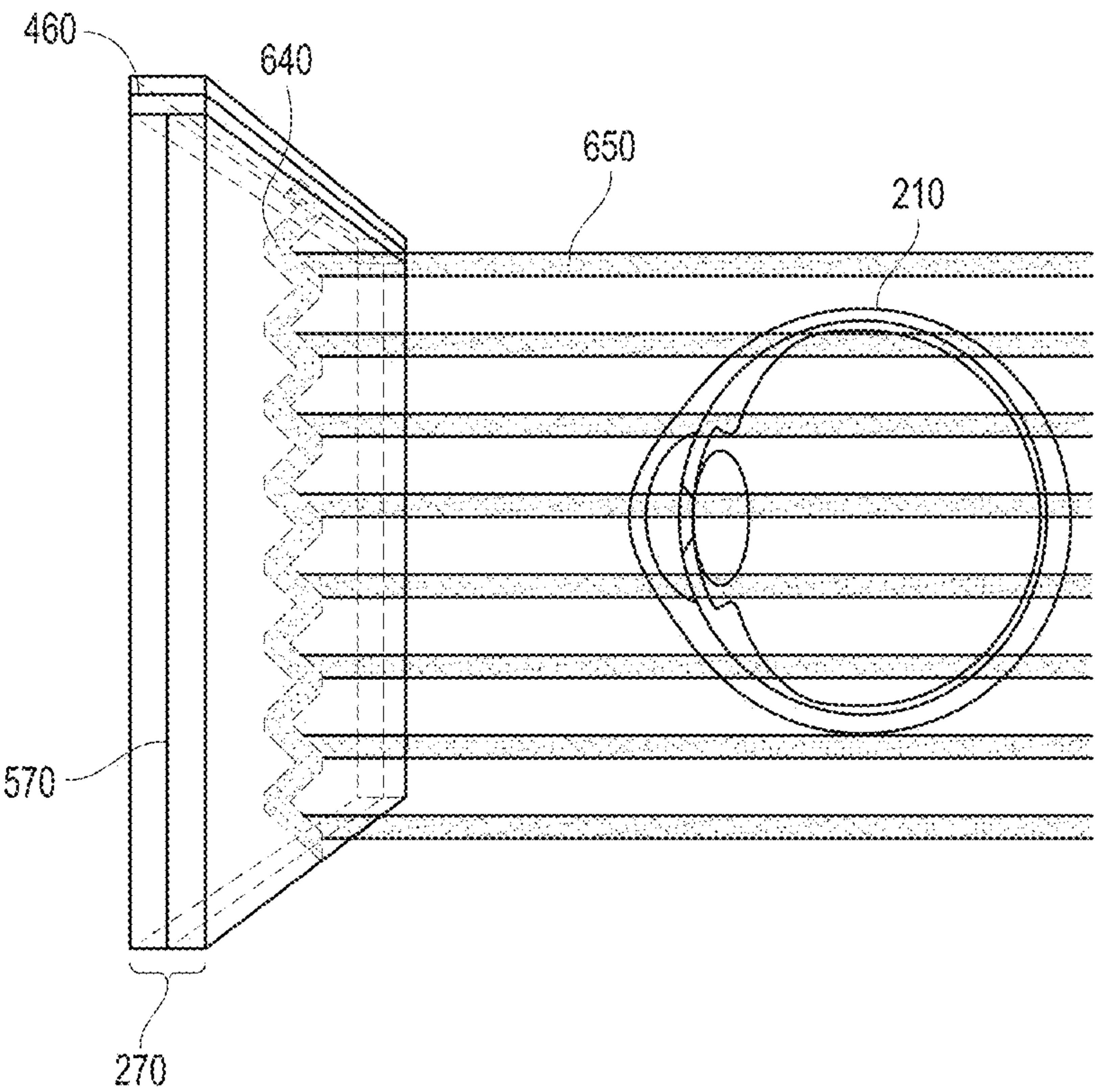


FIG. 7

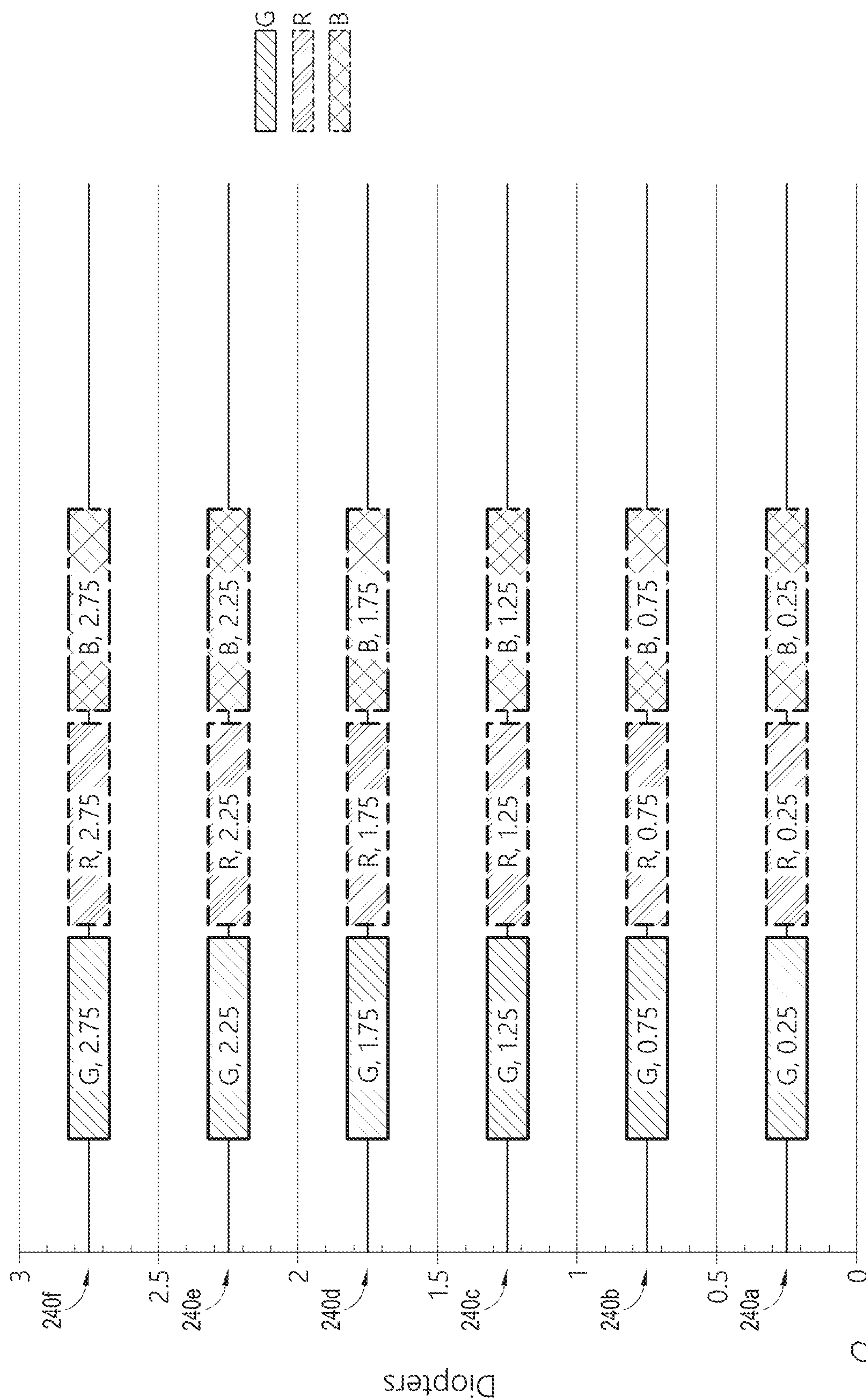


FIG. 8

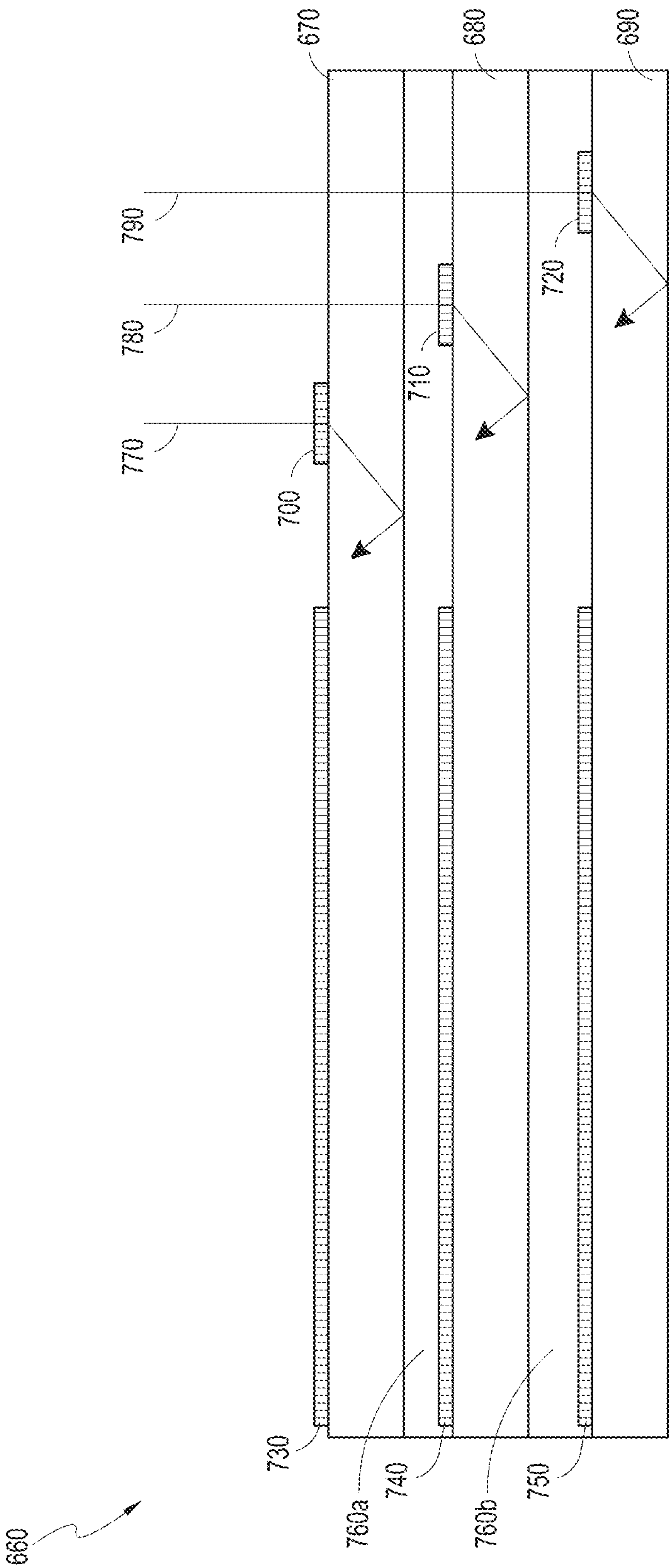


FIG. 9A

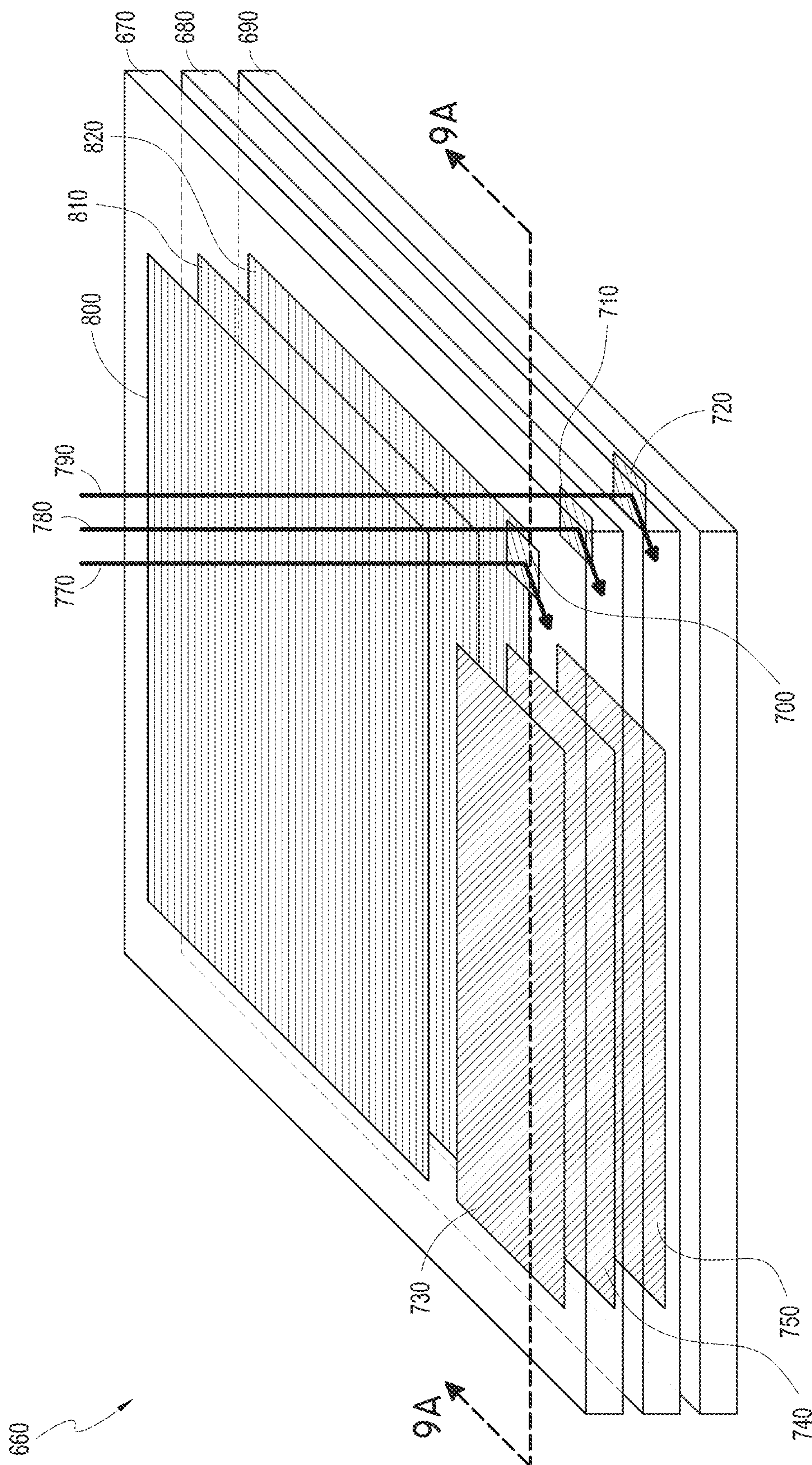


FIG. 9B

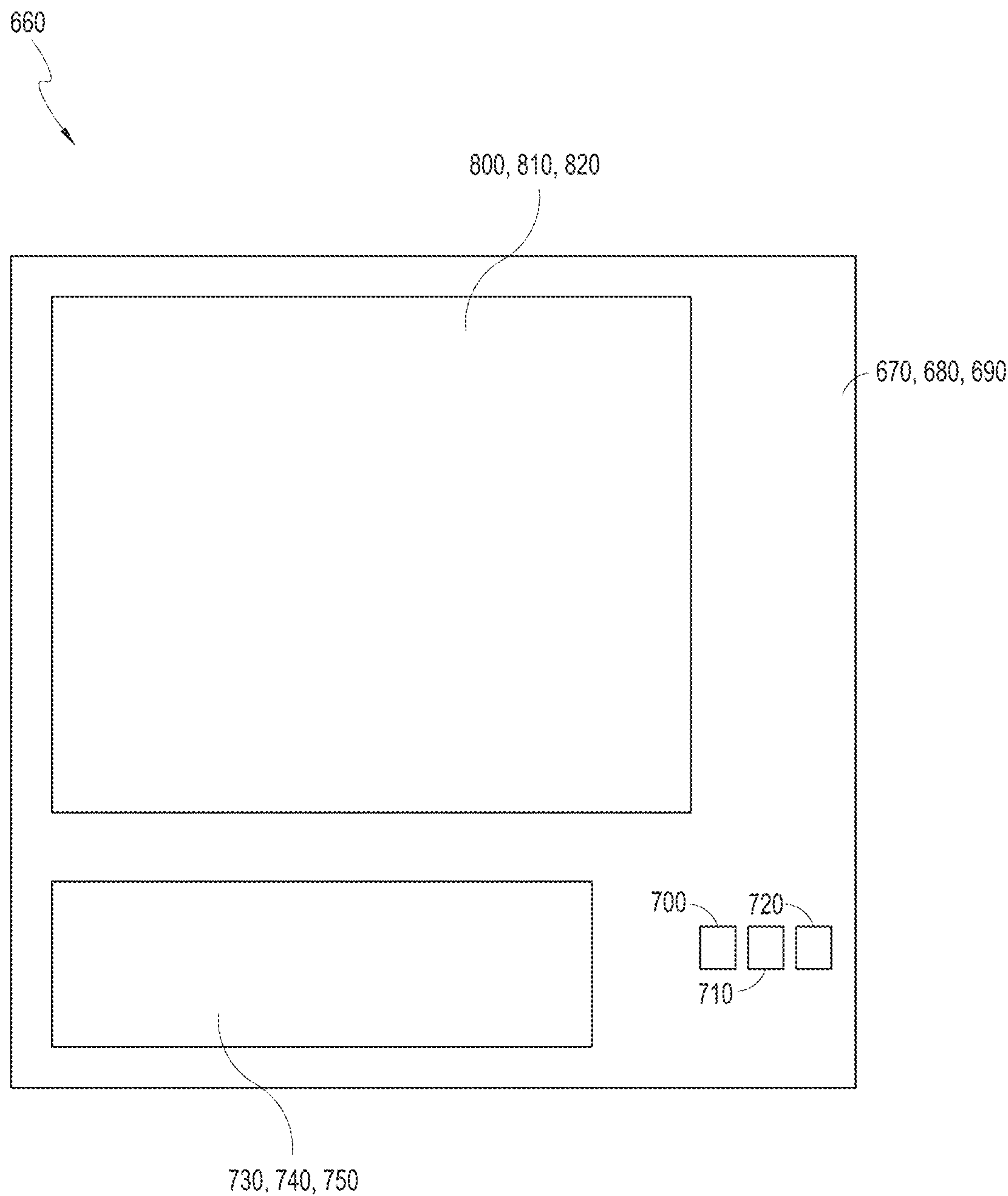


FIG. 9C

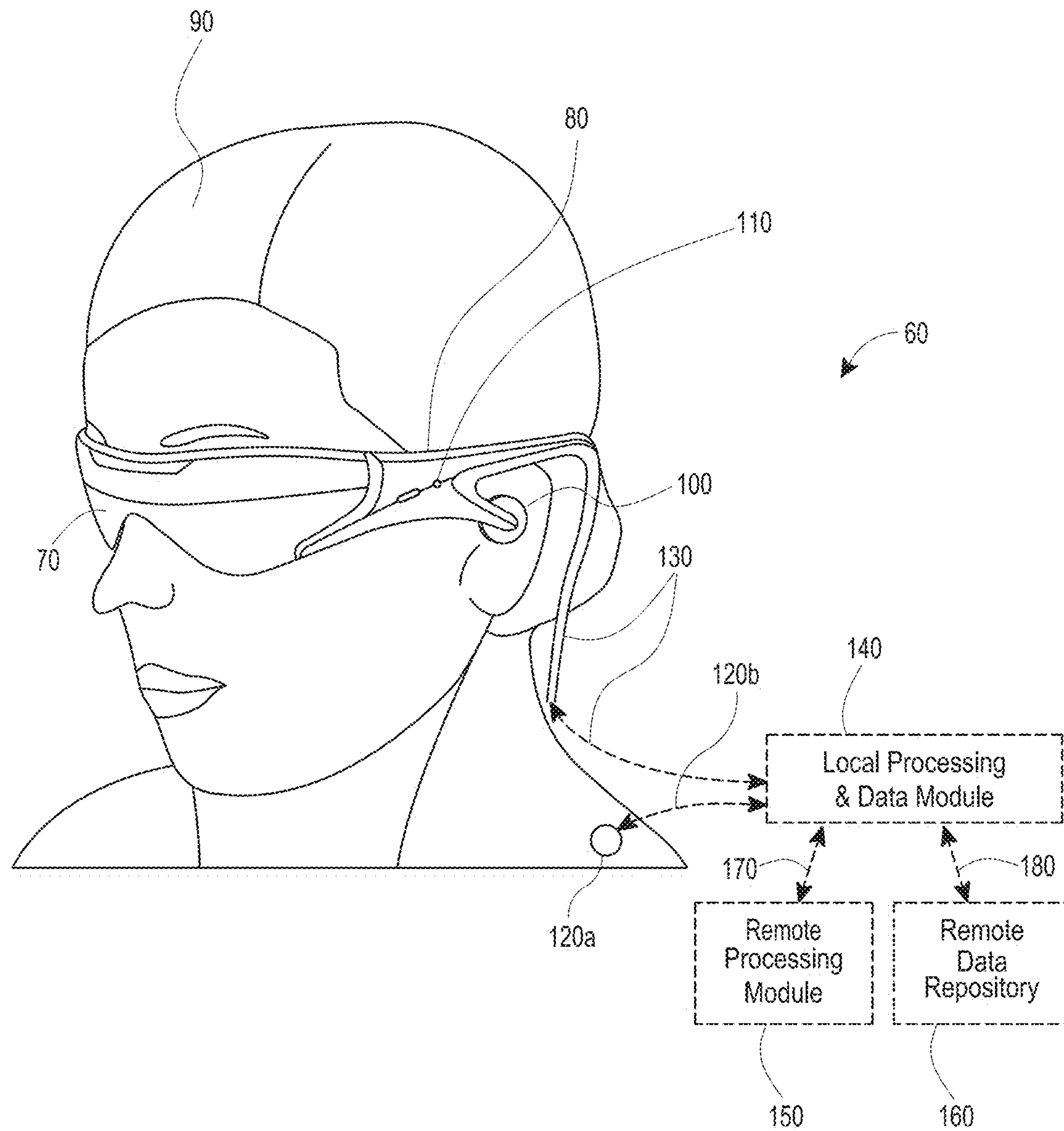
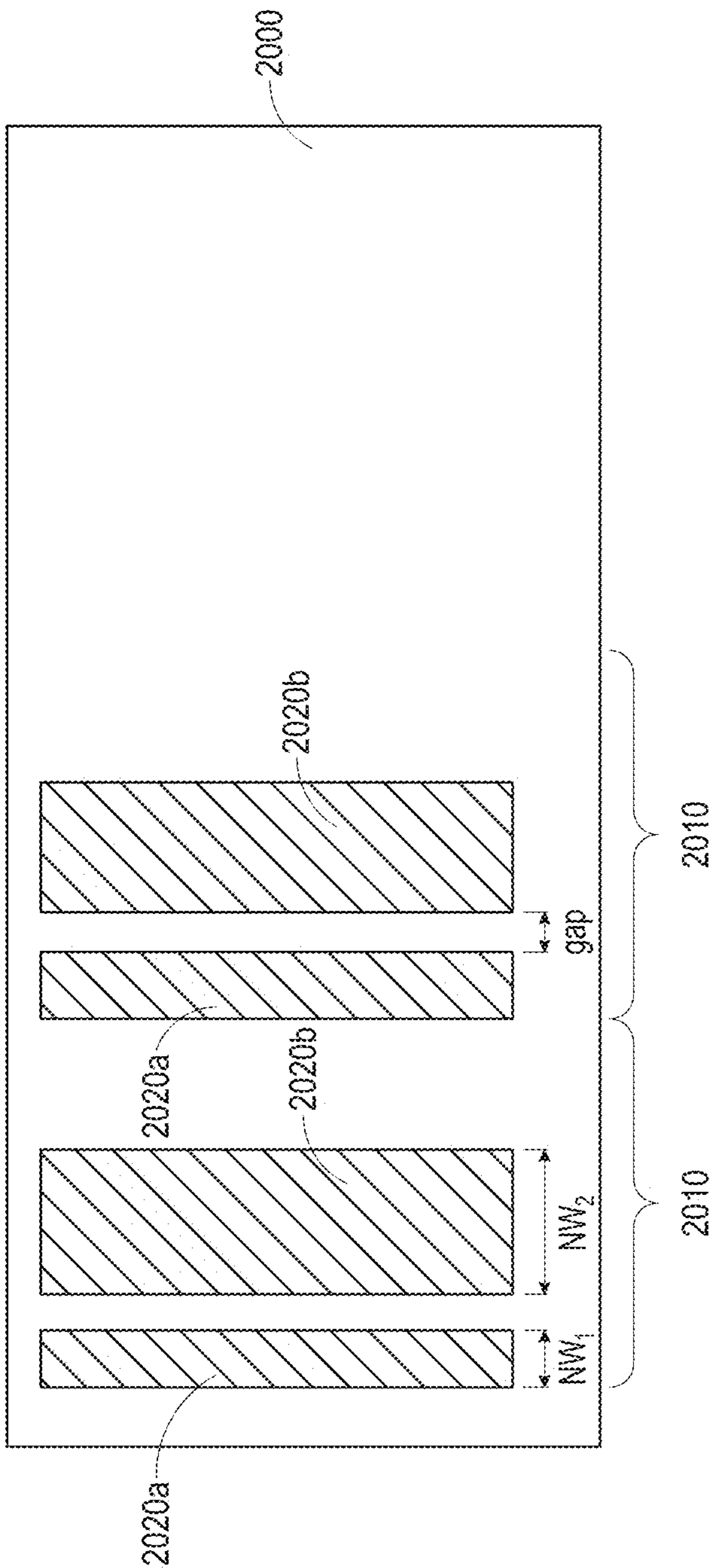
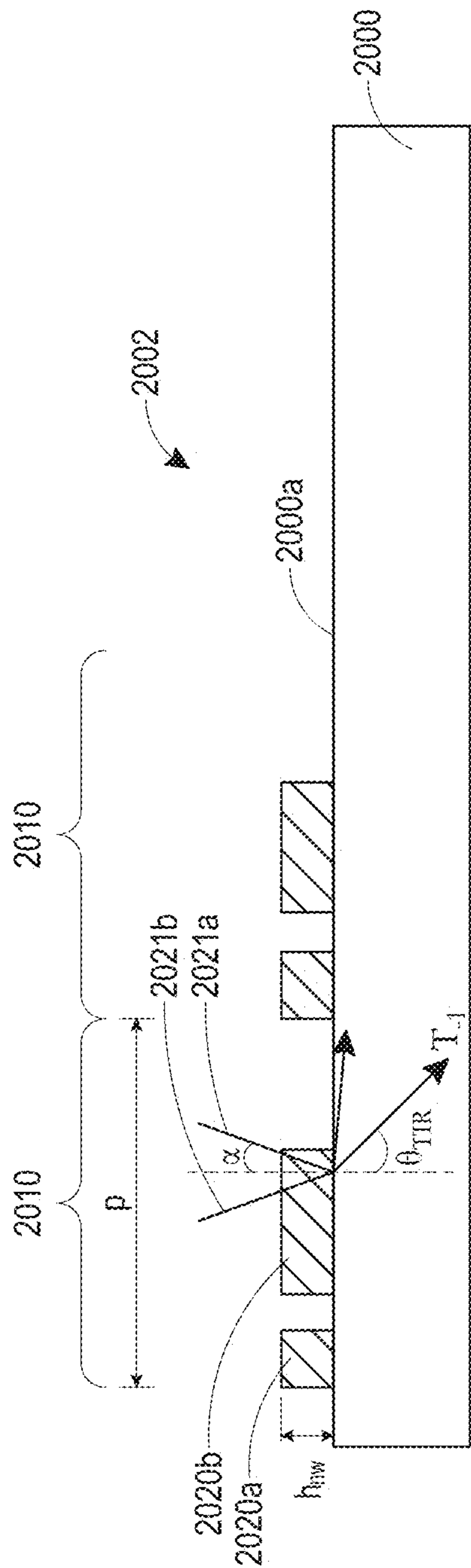
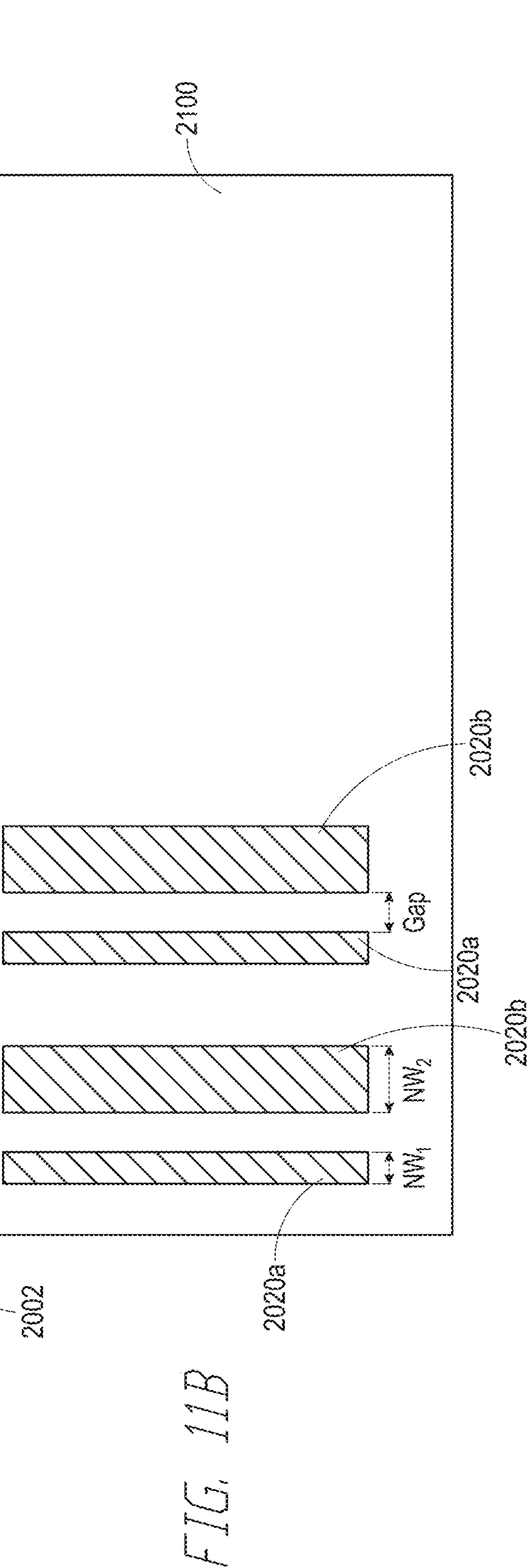
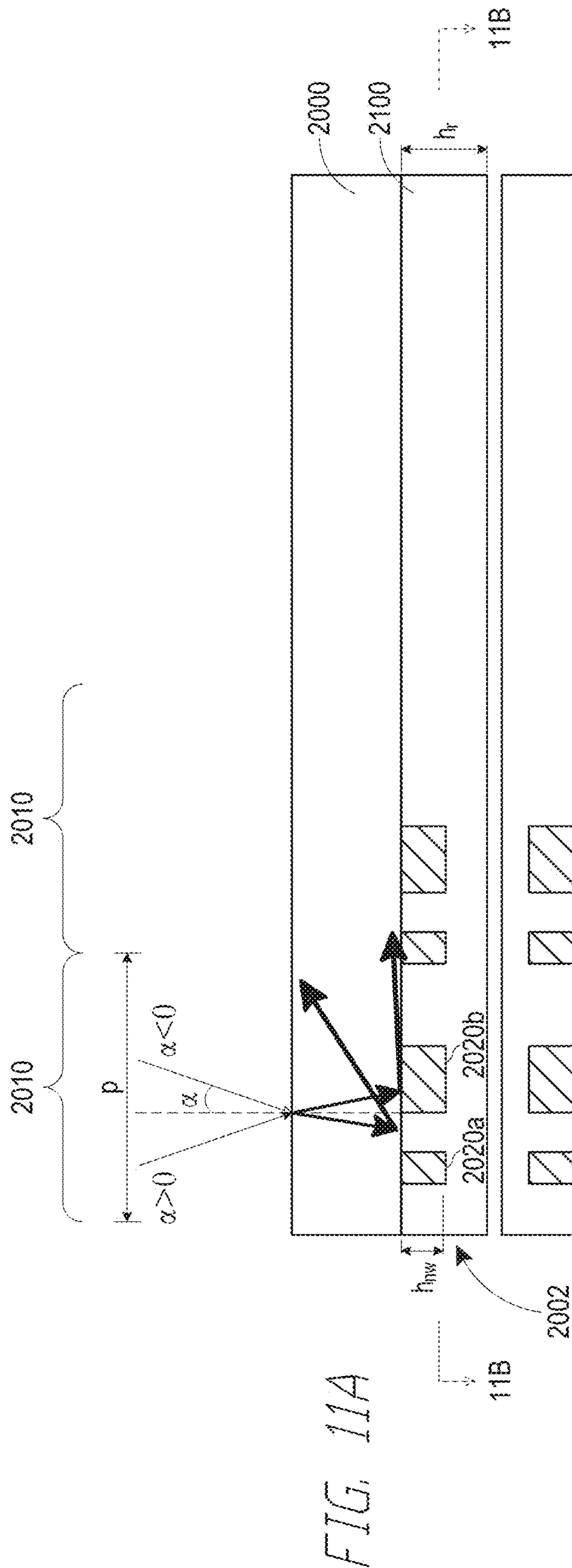


FIG. 9D





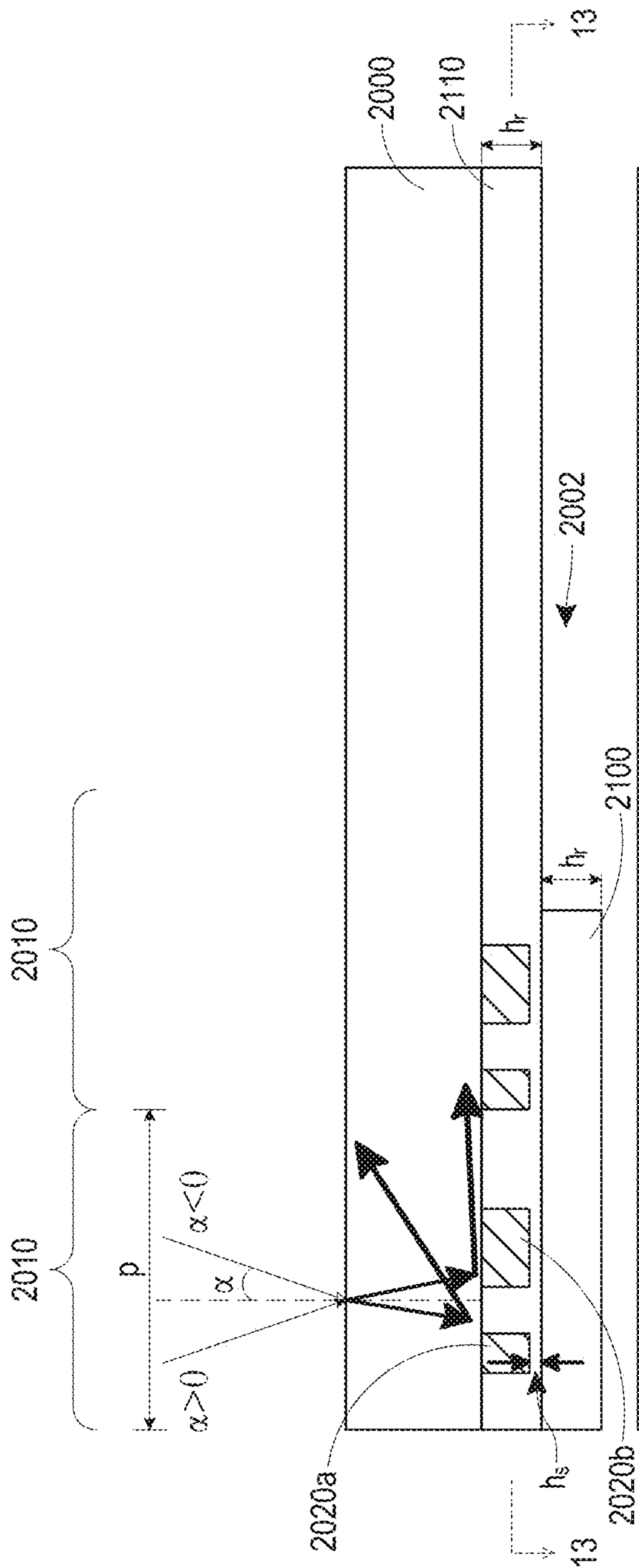


FIG. 12

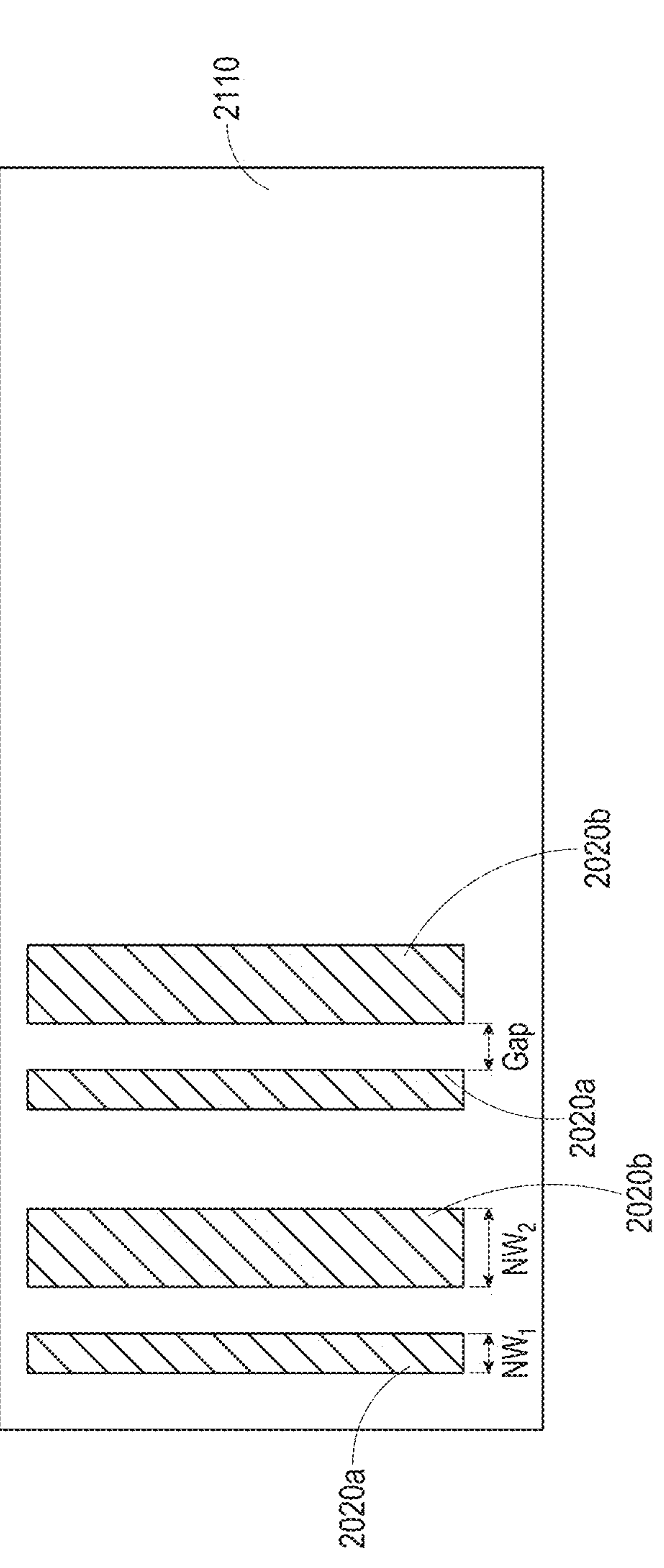
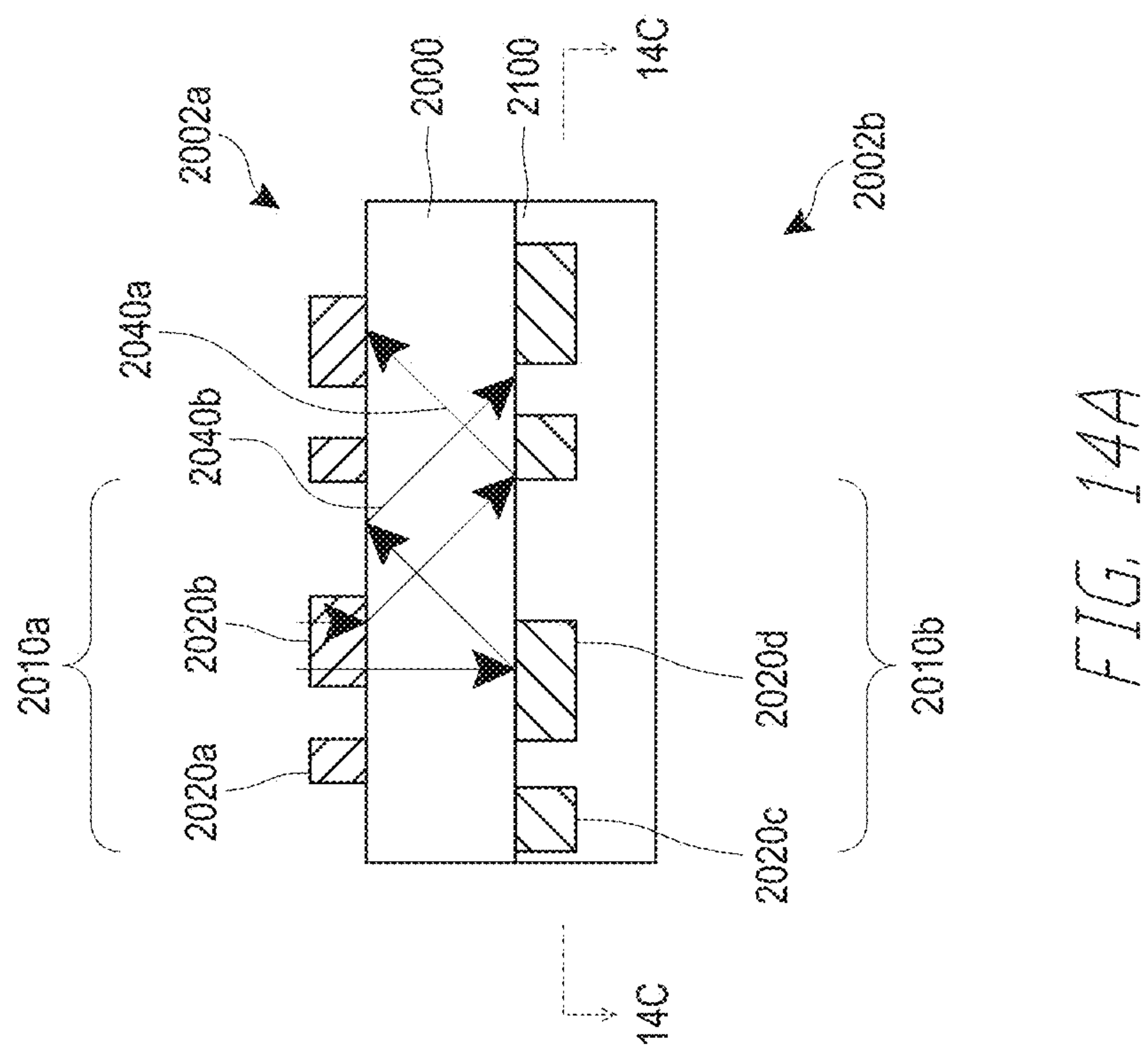
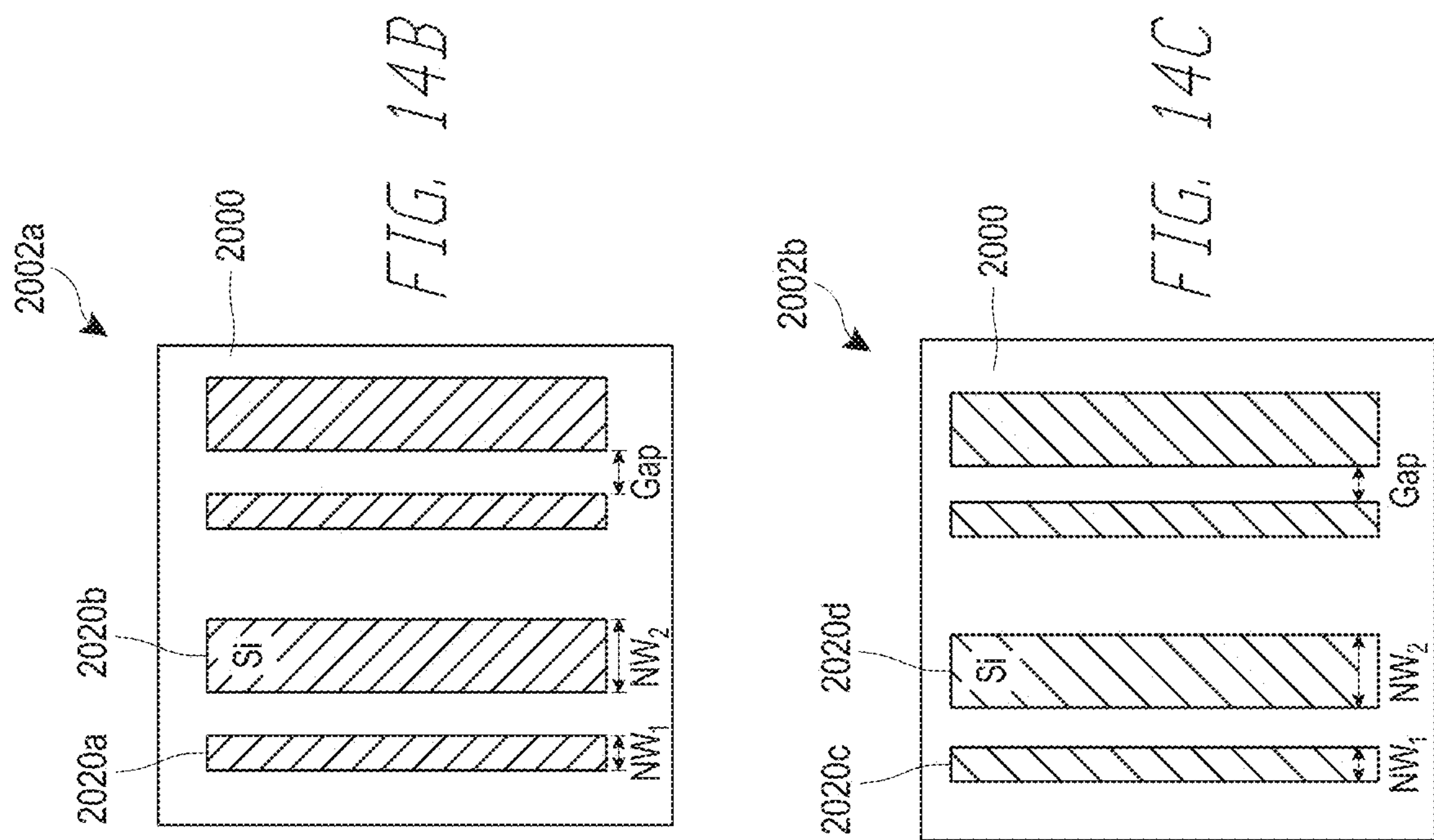


FIG. 13



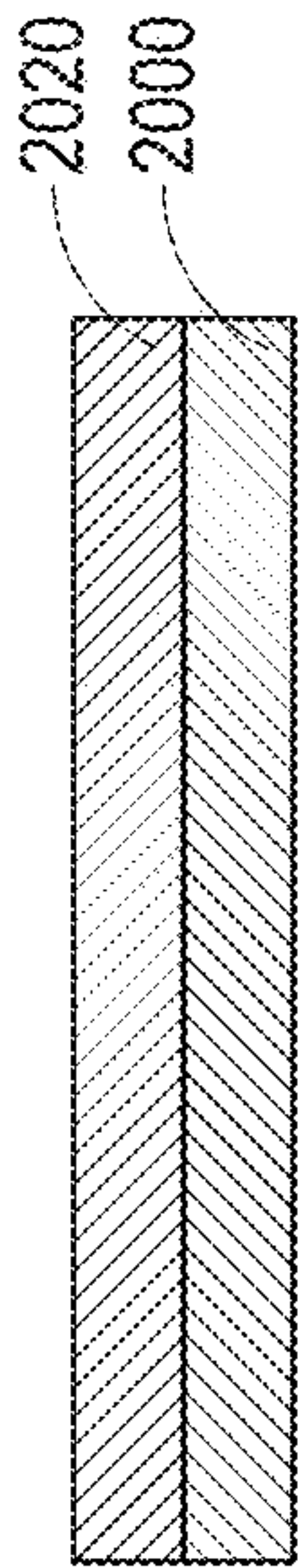


FIG. 15A

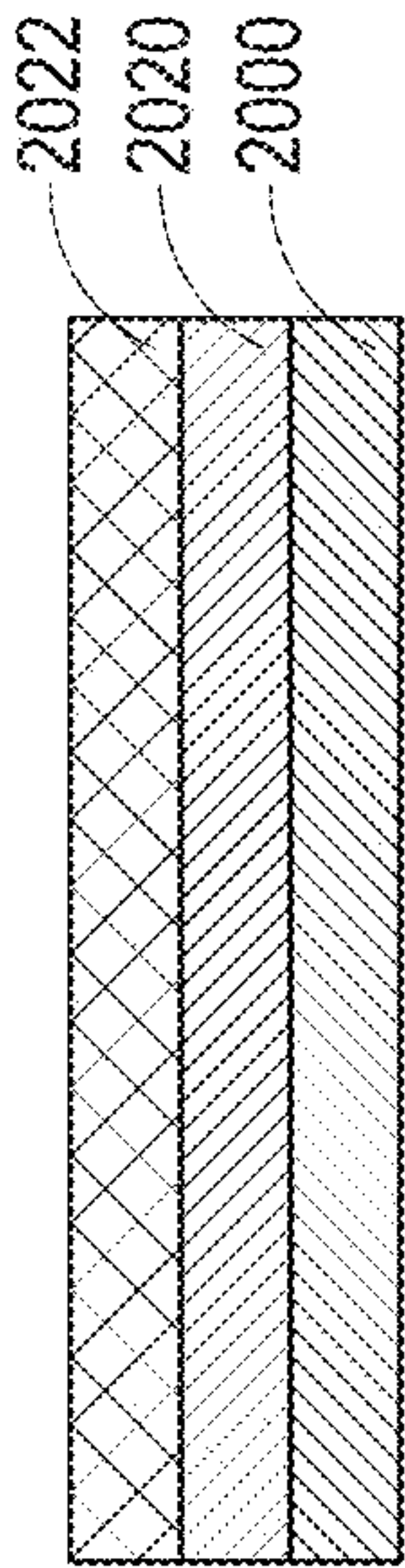


FIG. 15B

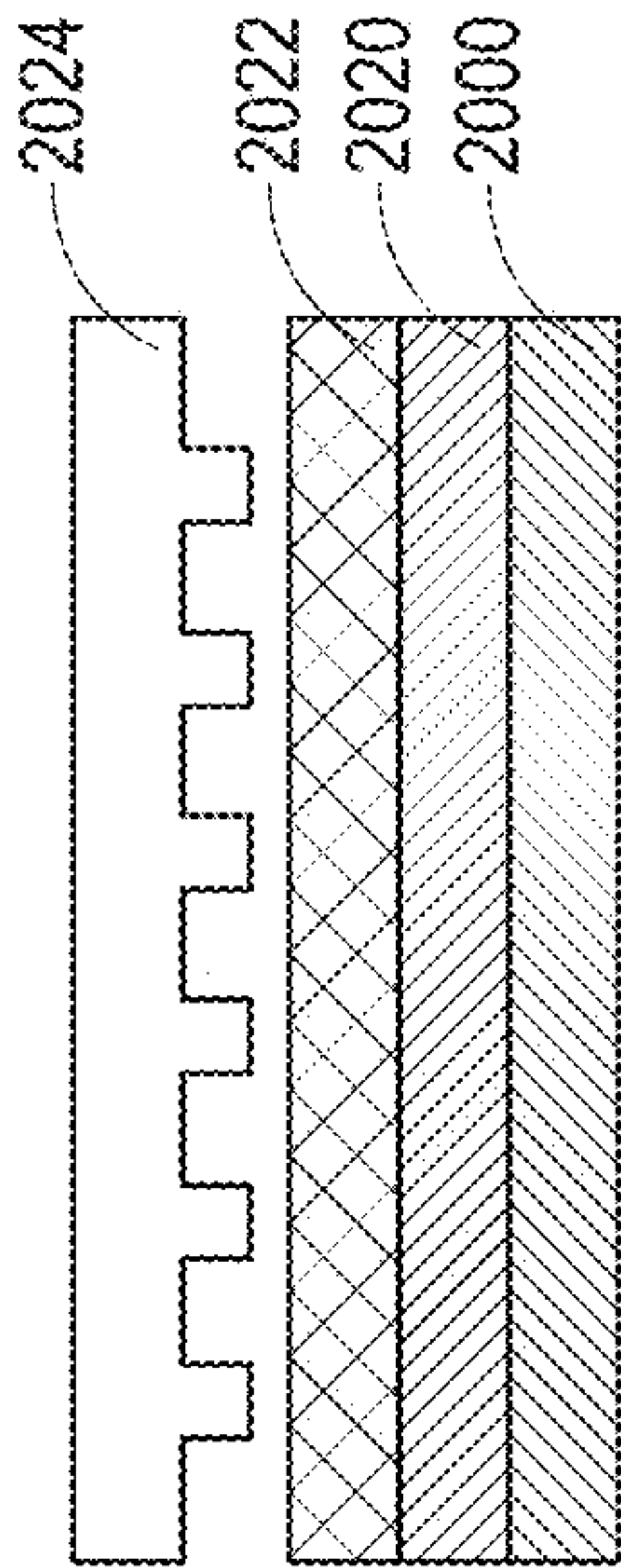


FIG. 15C

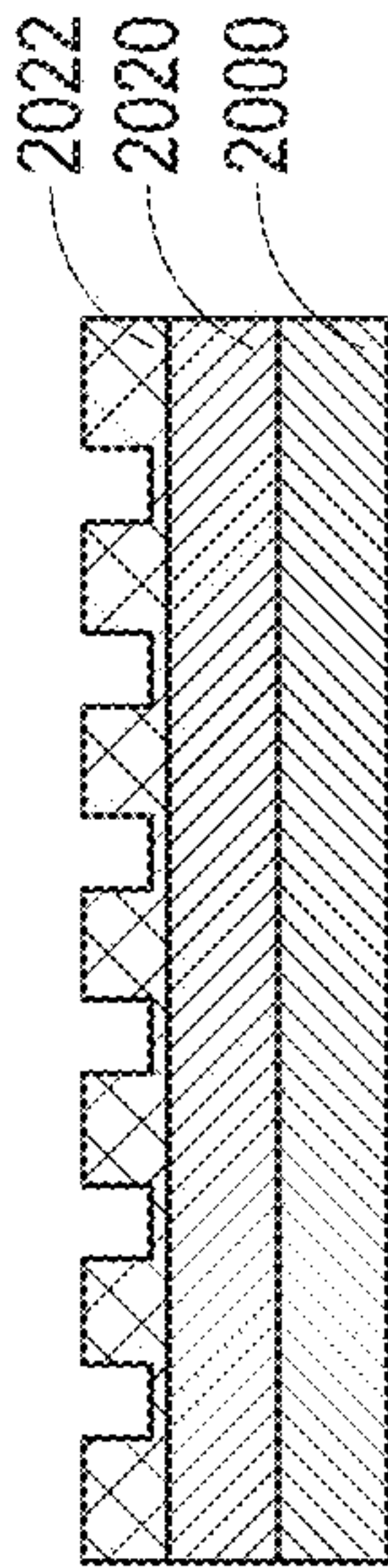


FIG. 15D

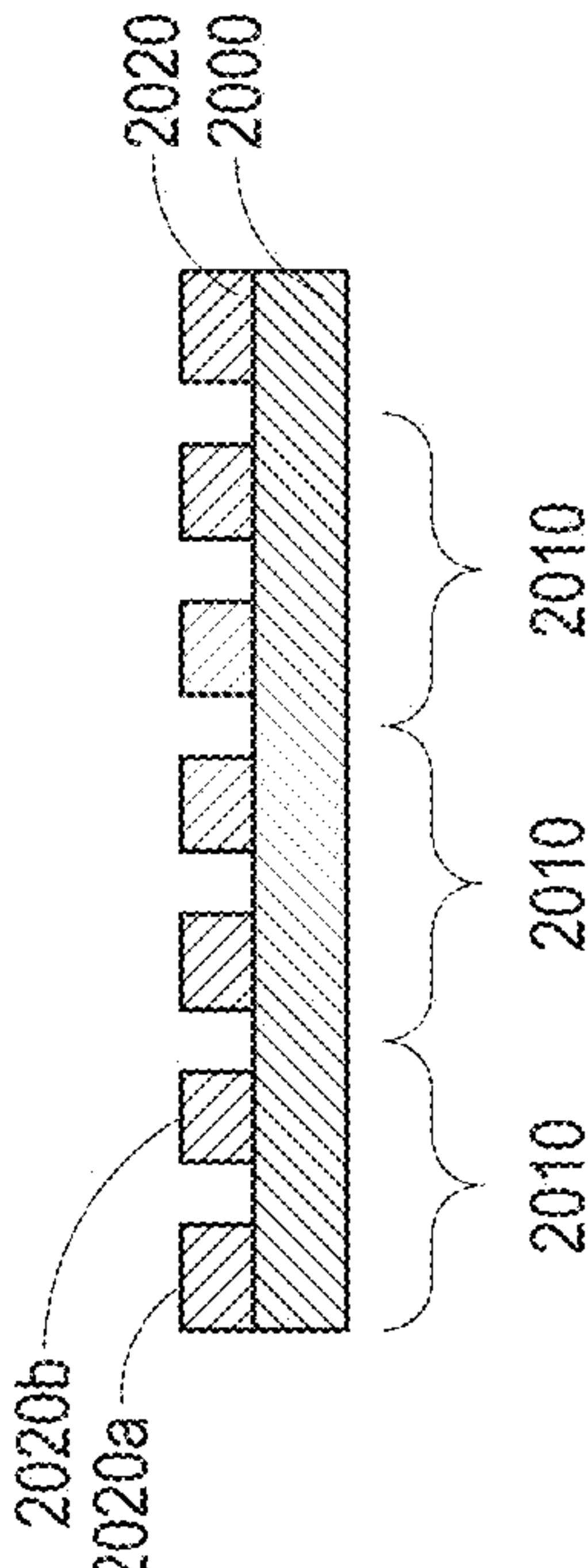


FIG. 15E

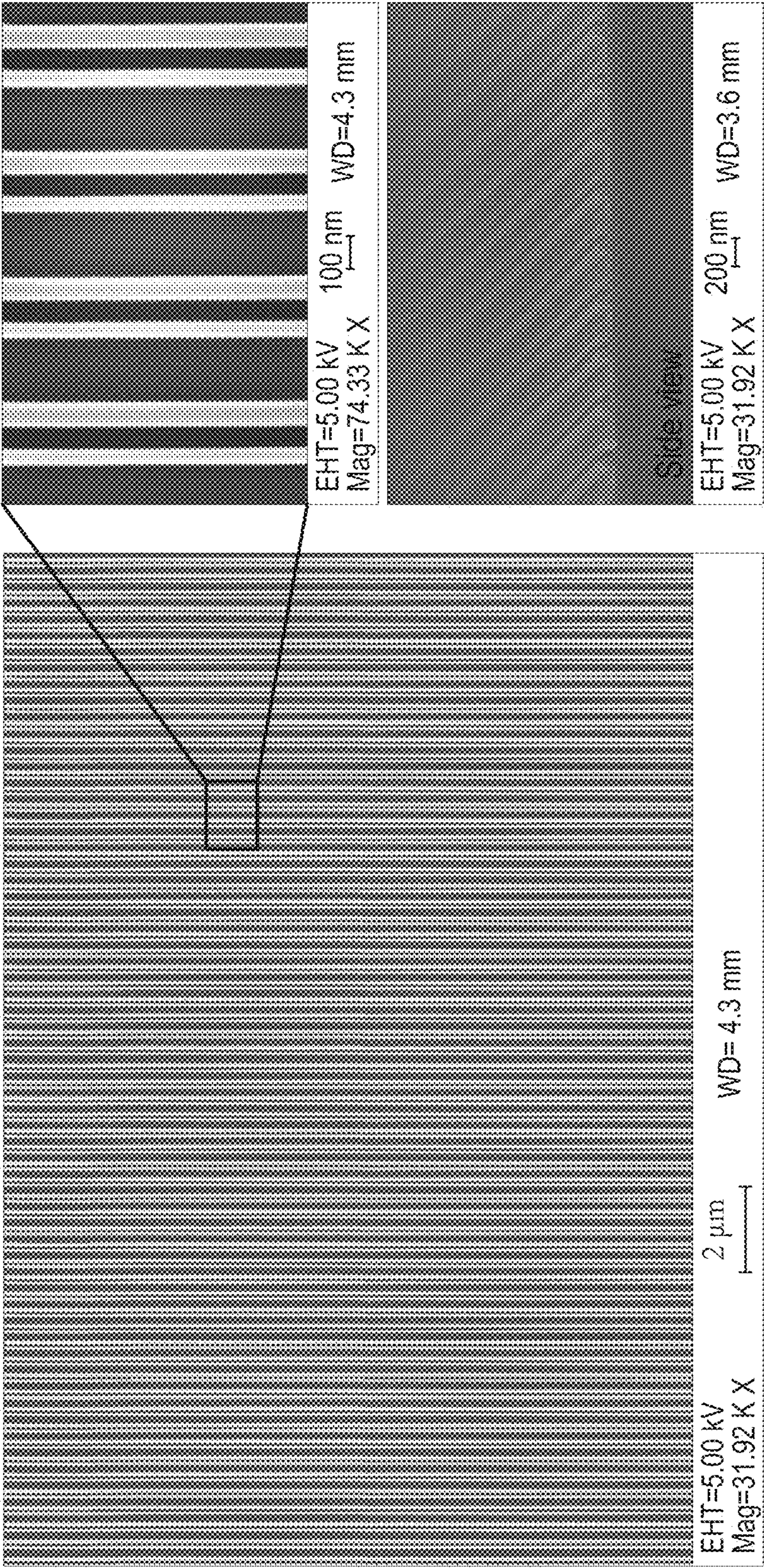


FIG. 16B

FIG. 16A

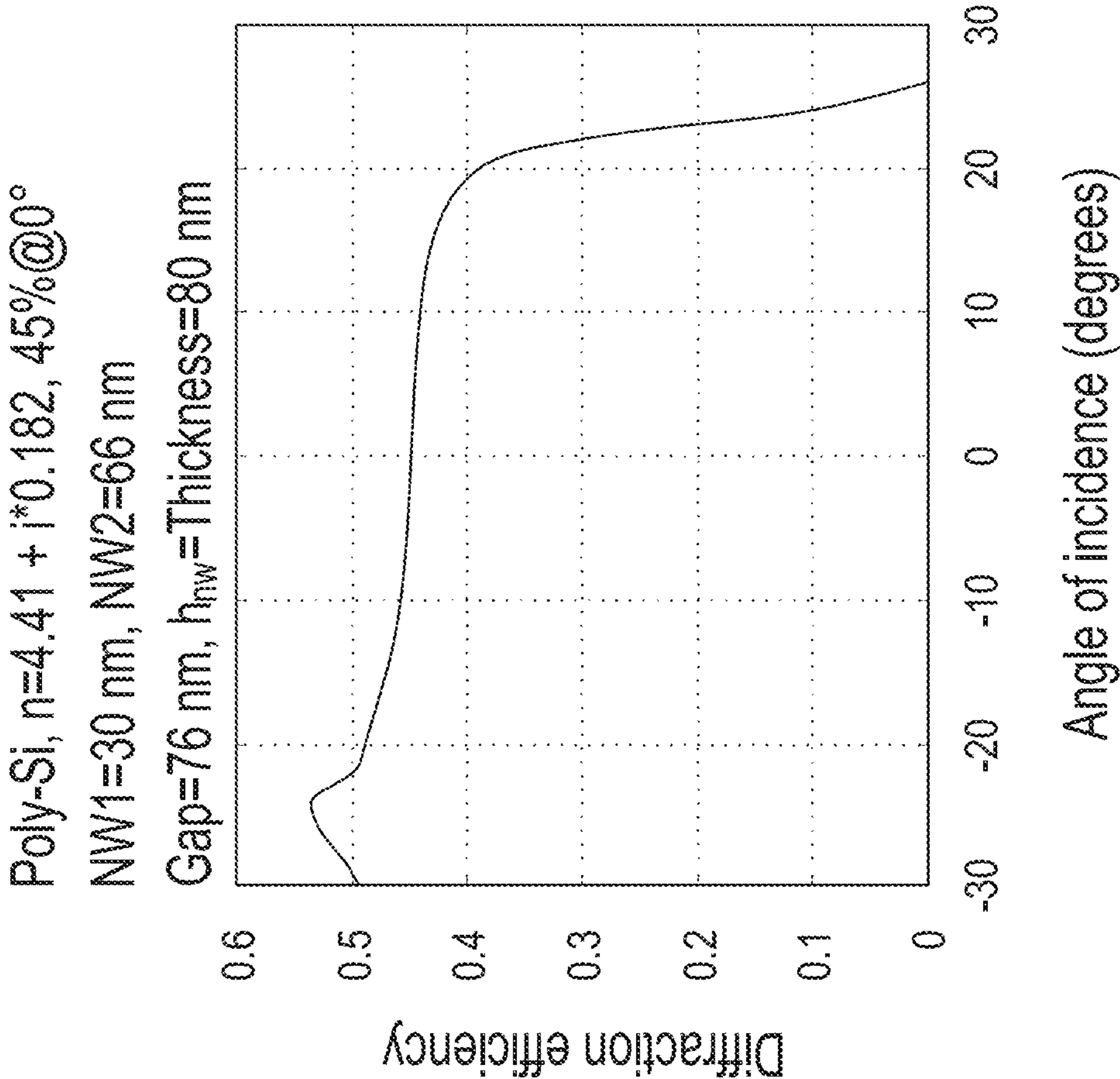


FIG. 17

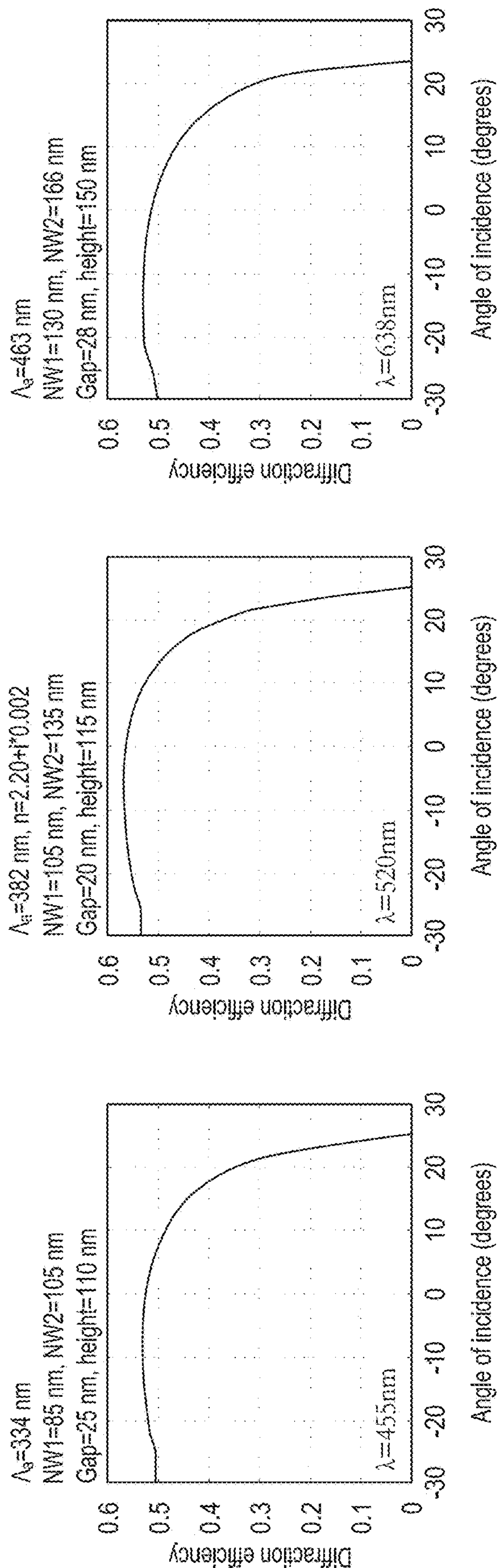


FIG. 18A

FIG. 18B

FIG. 18C

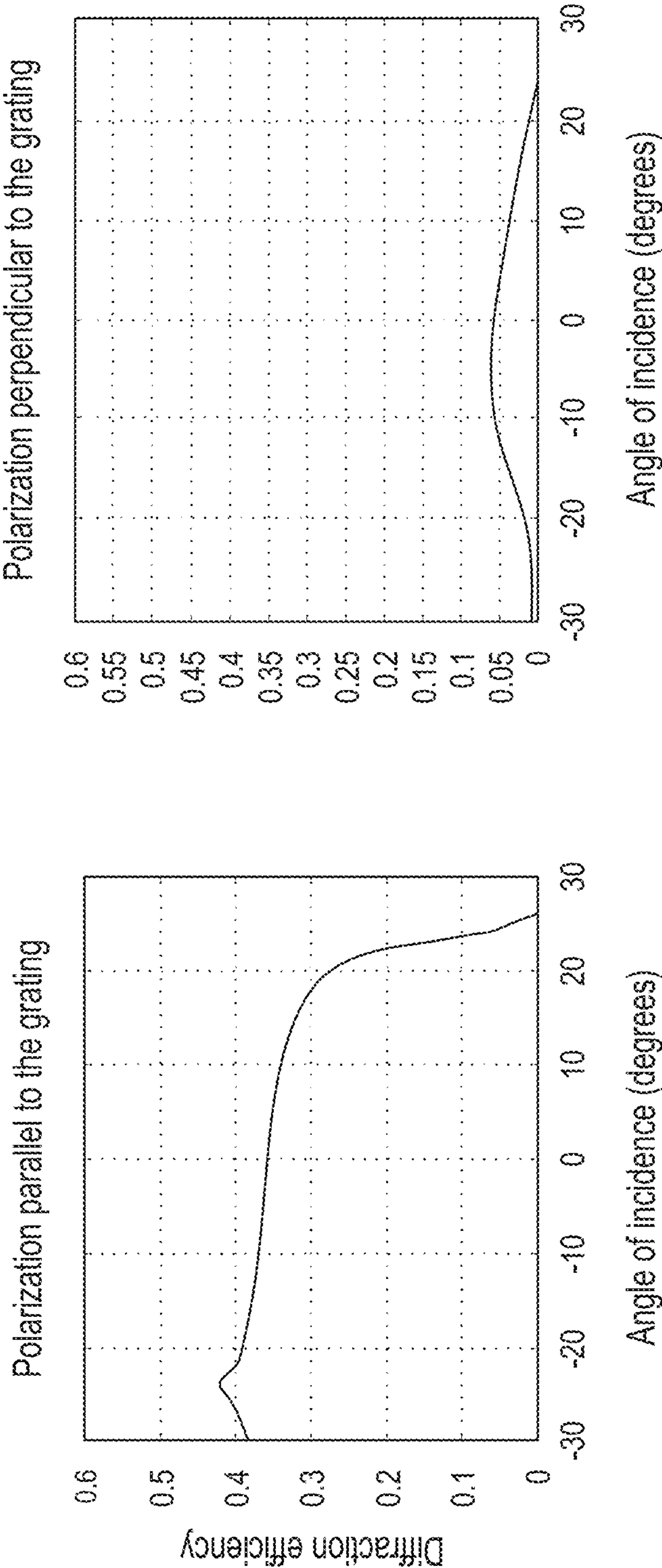


FIG. 19A

FIG. 19B

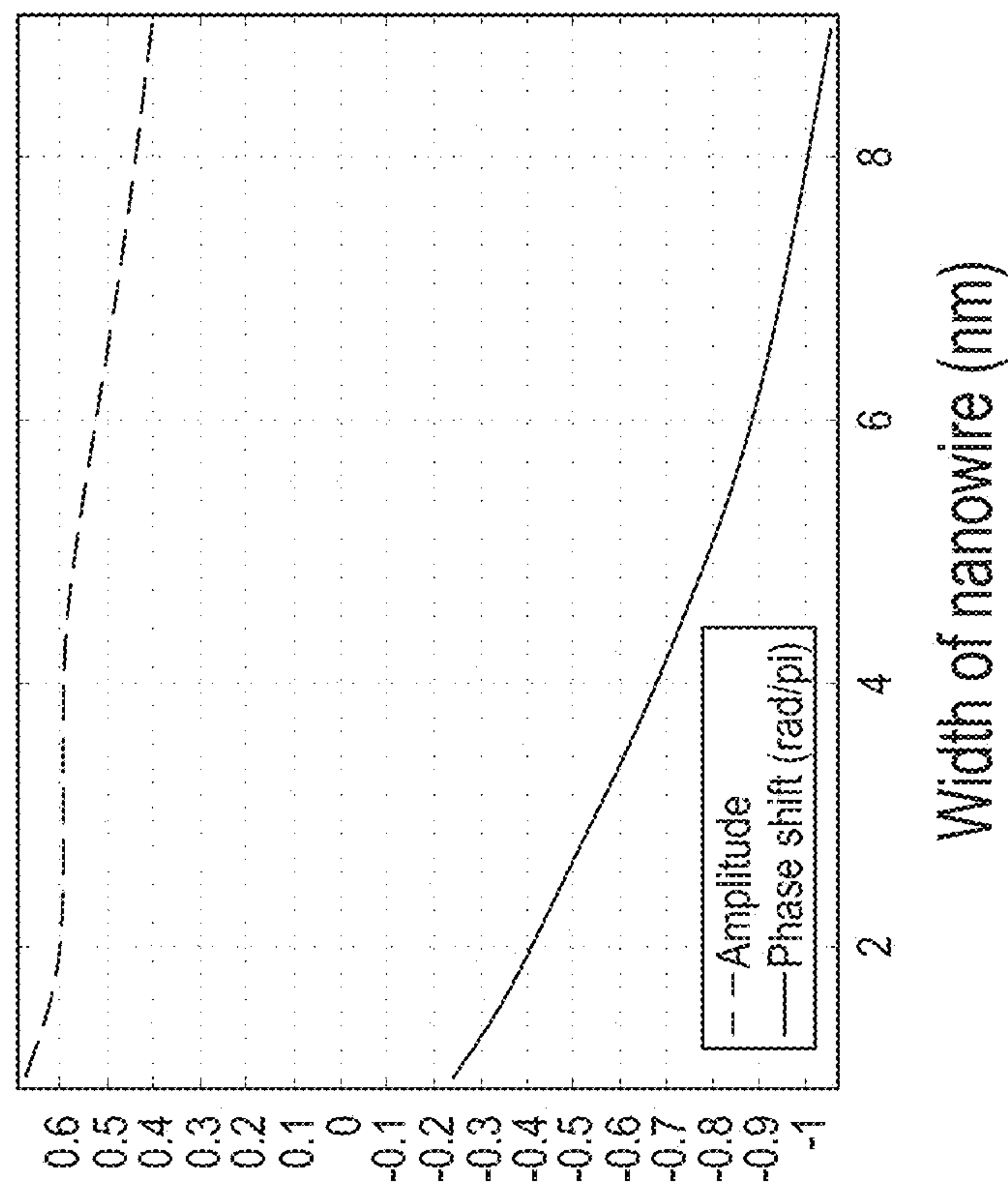


FIG. 20

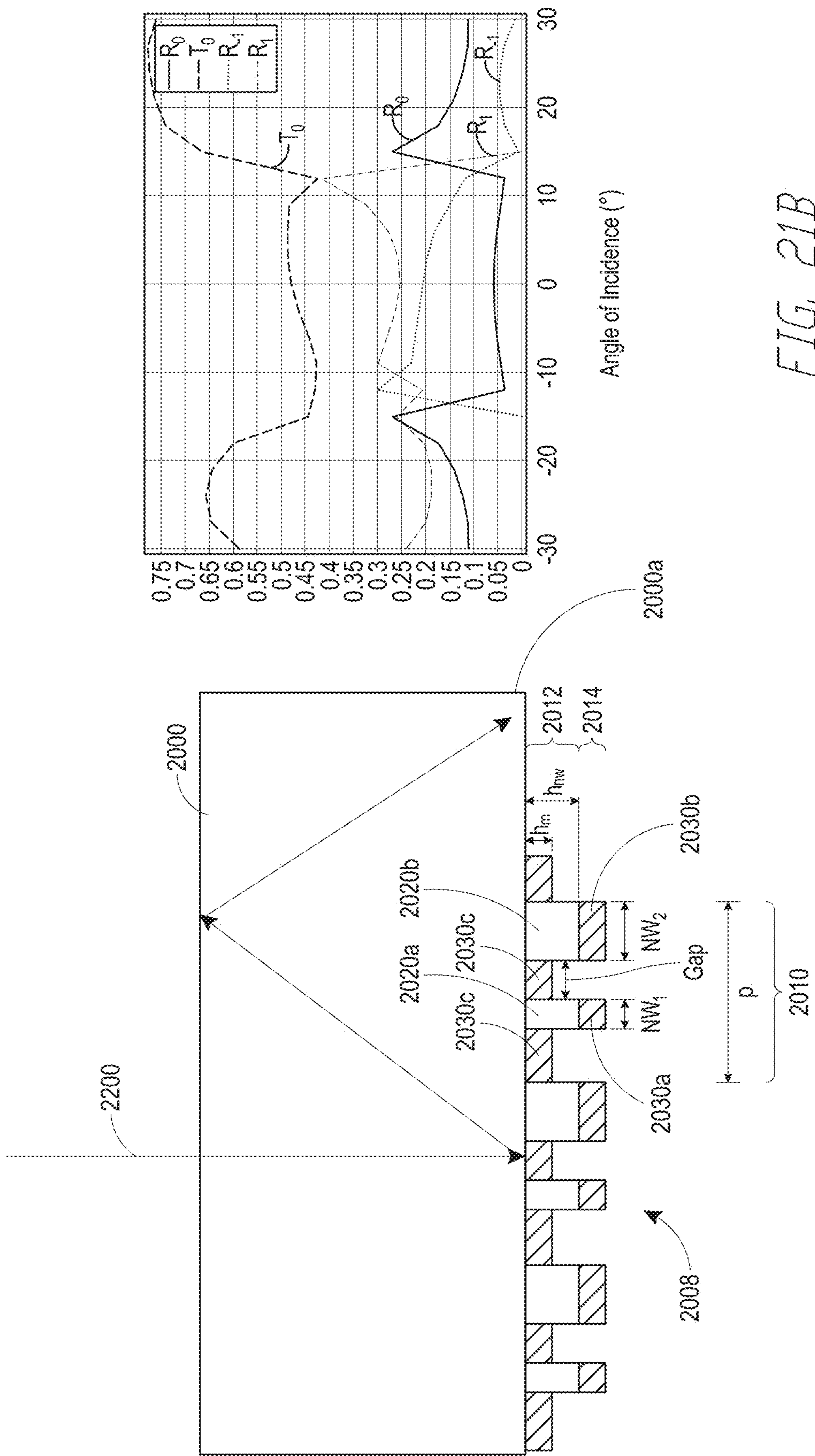


FIG. 21A

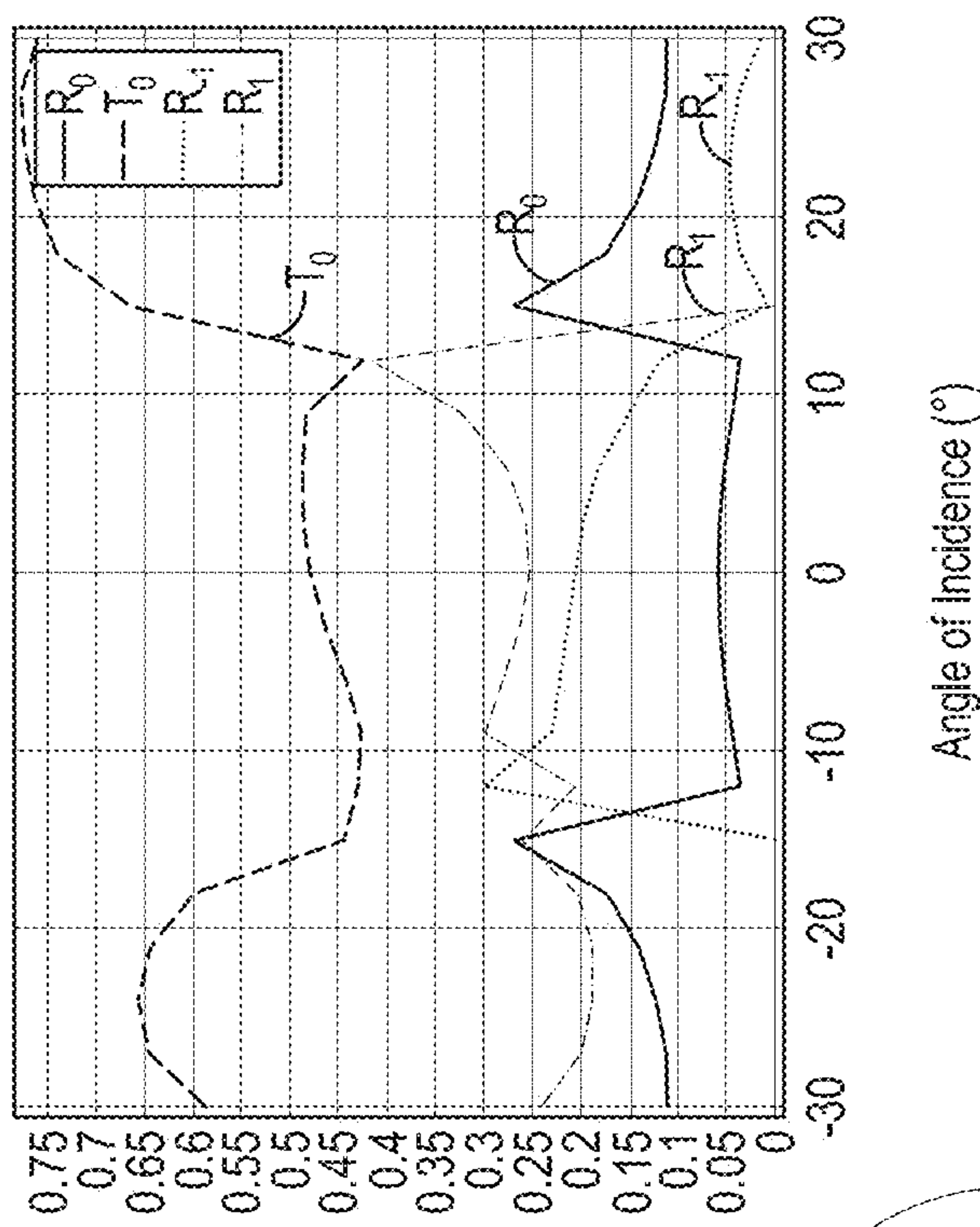


FIG. 21B

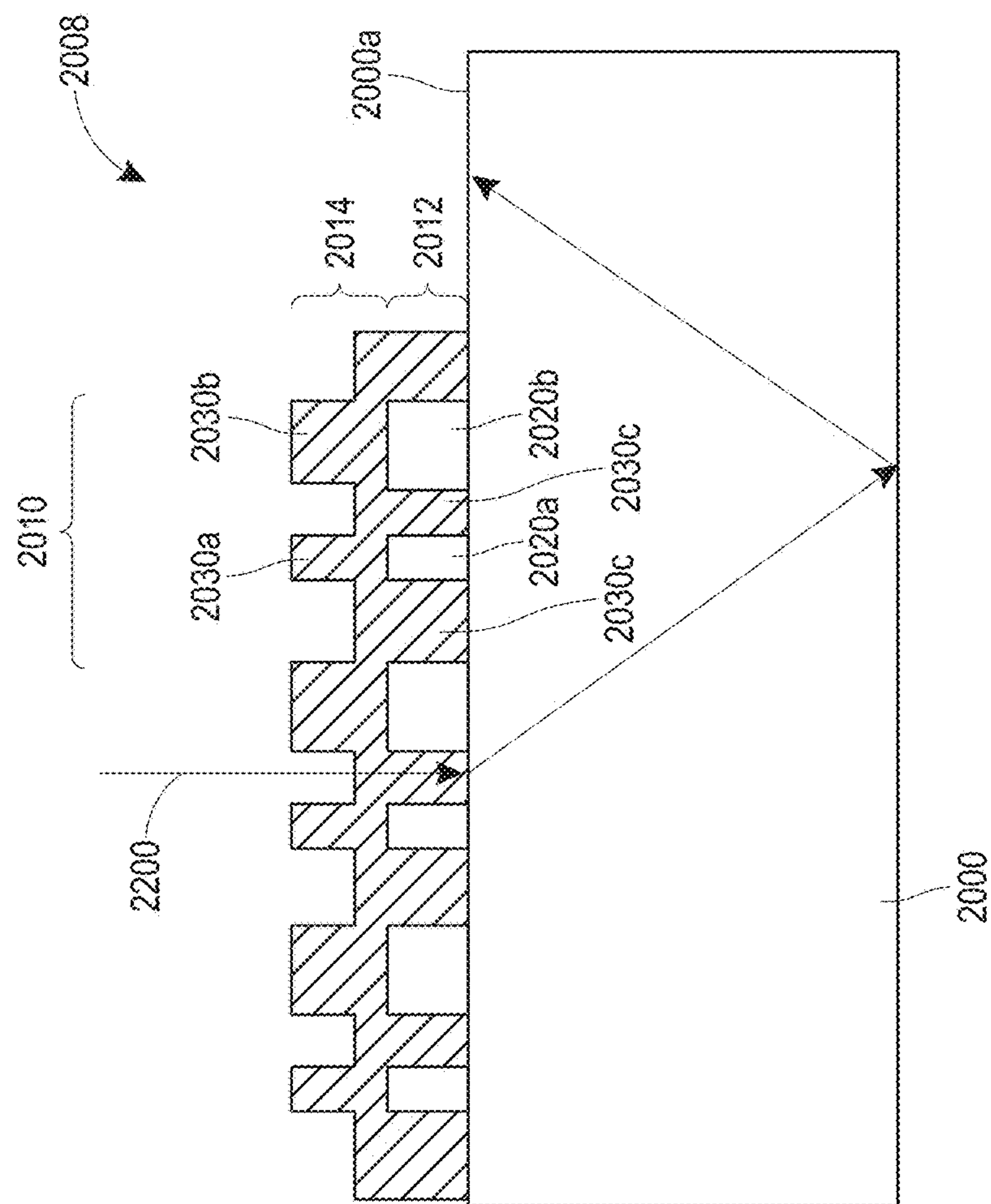


FIG. 22A

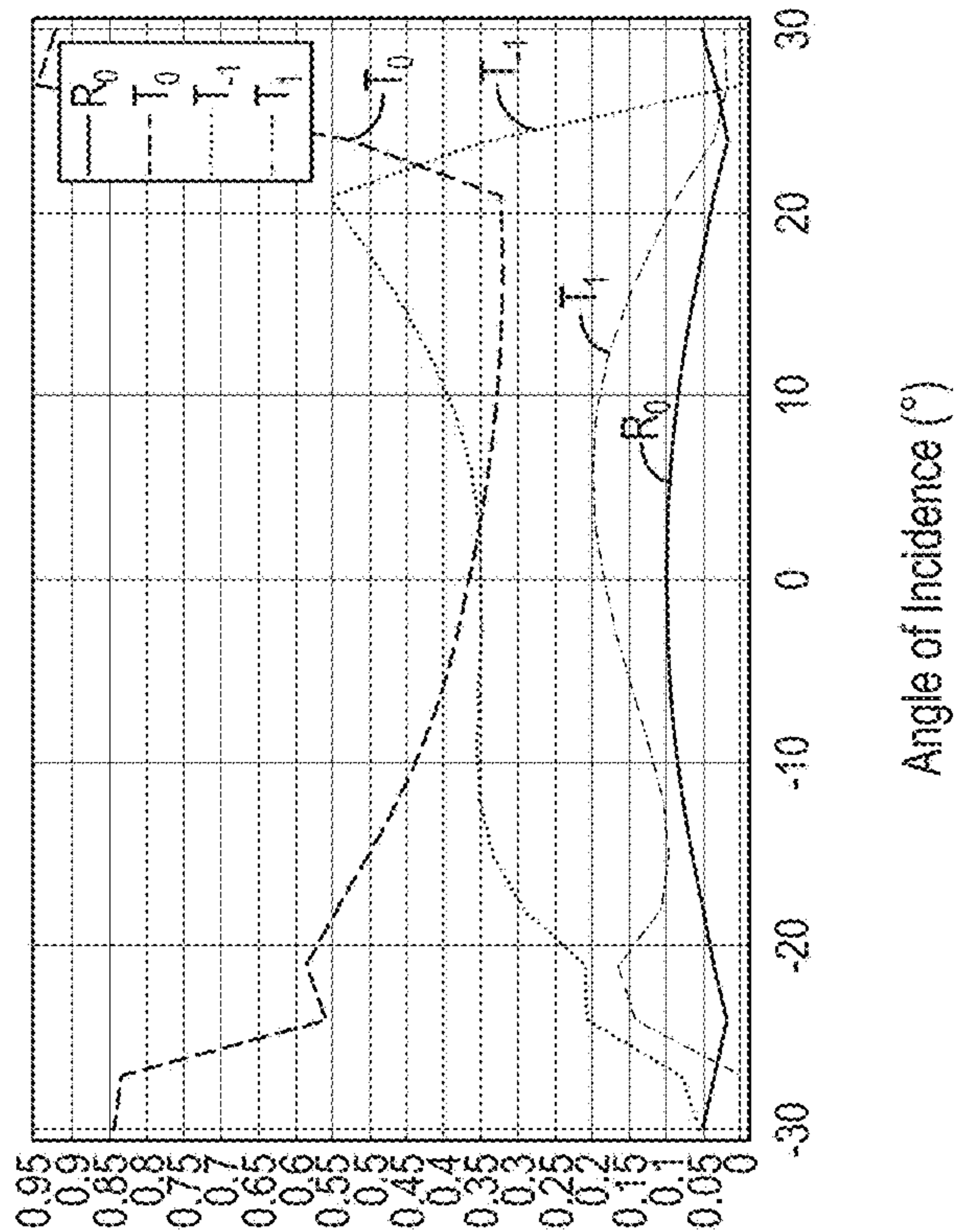


FIG. 22B

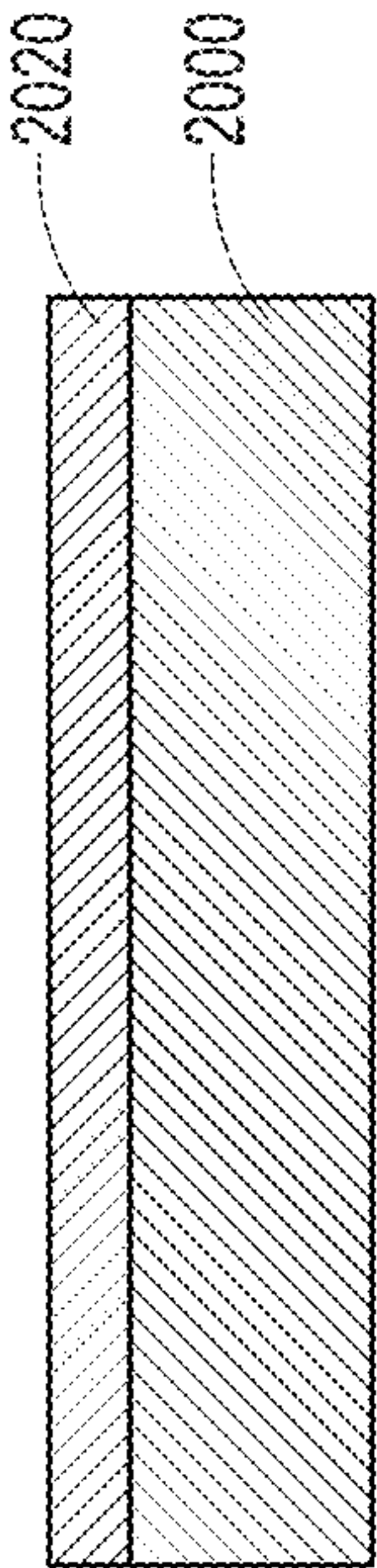


FIG. 23A

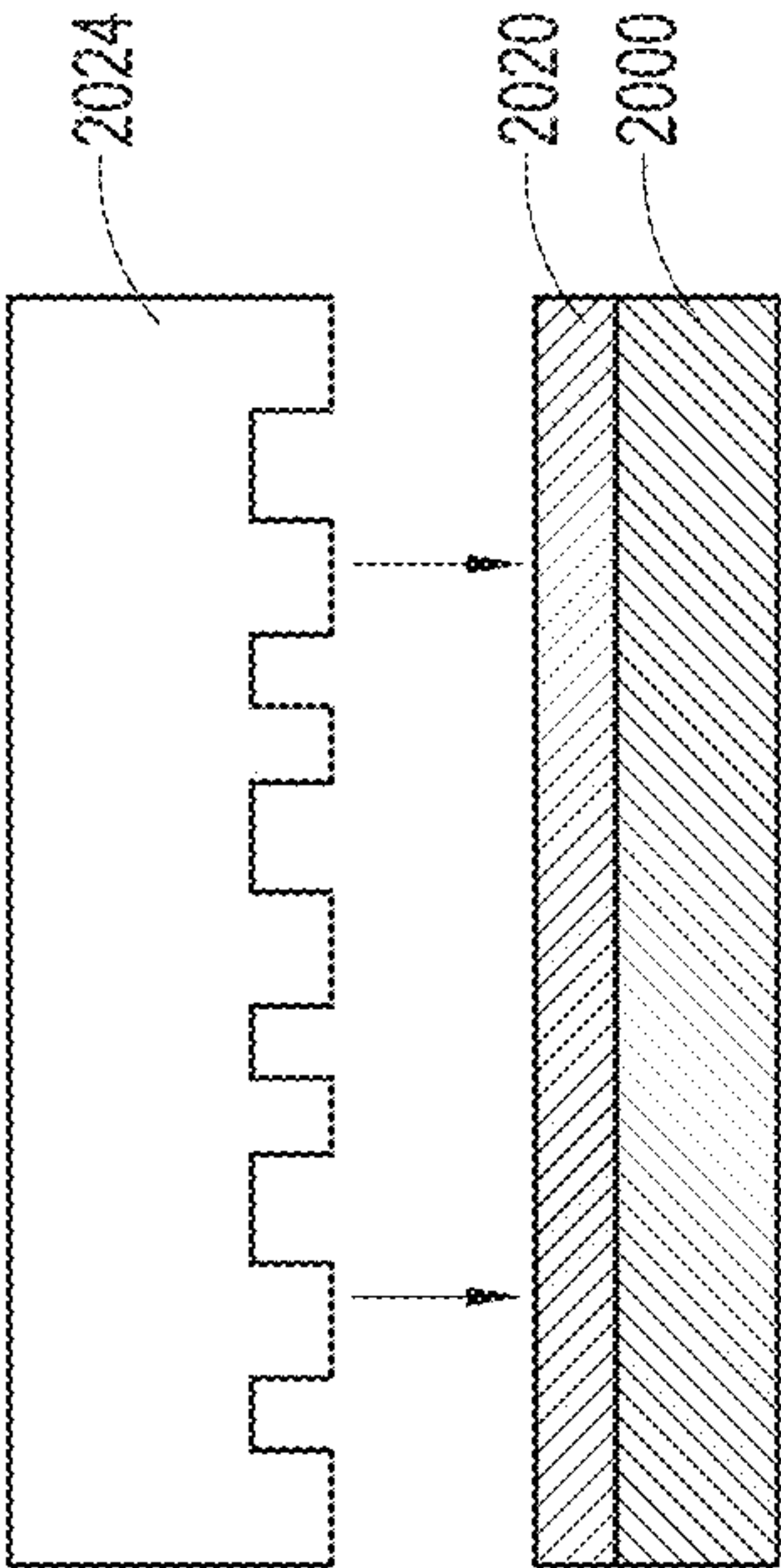


FIG. 23B

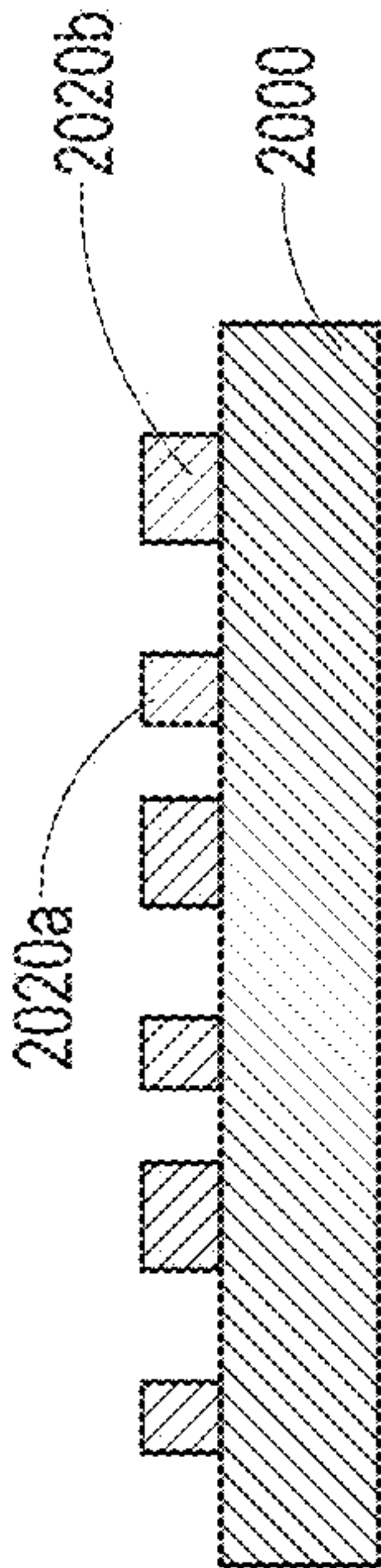


FIG. 23C

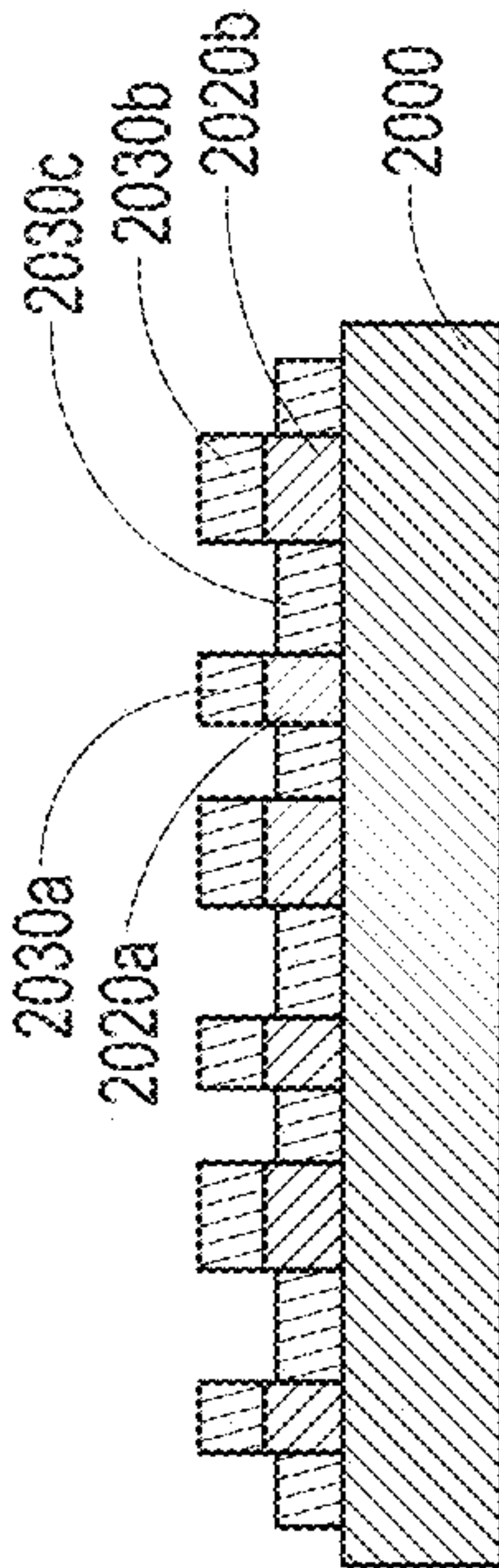


FIG. 23D

METASURFACES WITH ASYMETRIC GRATINGS FOR REDIRECTING LIGHT AND METHODS FOR FABRICATING

PRIORITY CLAIM

This application is a continuation of U.S. application Ser. No. 16/733,168, filed on Jan. 2, 2020, which is a divisional of U.S. application Ser. No. 15/588,350, filed on May 5, 2017, which claims the benefit of priority under 35 U.S.C. § 119(e) of: U.S. Provisional Application No. 62/333,067, filed on May 6, 2016; and U.S. Patent Application No. 62/474,432, filed on Mar. 21, 2017. The entire disclosure of each of these priority documents is incorporated herein by reference.

INCORPORATION BY REFERENCE

This application incorporates by reference the entirety of each of the following patent publications: U.S. Publication No. 2015/0016777; U.S. Publication No. 2015/0178939; and U.S. Publication No. 2015/0346490.

BACKGROUND

Field

The present disclosure relates to optical devices, including augmented reality imaging and visualization systems.

Description of the Related Art

Modern computing and display technologies have facilitated the development of systems for so called “virtual reality” or “augmented reality” experiences, in which digitally reproduced images or portions thereof are presented to a user in a manner wherein they seem to be, or may be perceived as, real. A virtual reality, or “VR”, scenario typically involves the presentation of digital or virtual image information without transparency to other actual real-world visual input; an augmented reality, or “AR”, scenario typically involves presentation of digital or virtual image information as an augmentation to visualization of the actual world around the user. A mixed reality, or “MR”, scenario is a type of AR scenario and typically involves virtual objects that are integrated into, and responsive to, the natural world. For example, an MR scenario may include AR image content that appears to be blocked by or is otherwise perceived to interact with objects in the real world.

Referring to FIG. 1, an augmented reality scene 10 is depicted. The user of an AR technology sees a real-world park-like setting 20 featuring people, trees, buildings in the background, and a concrete platform 30. The user also perceives that he/she “sees” “virtual content” such as a robot statue 40 standing upon the real-world platform 30, and a flying cartoon-like avatar character 50 which seems to be a personification of a bumble bee. These elements 50, 40 are “virtual” in that they do not exist in the real world. Because the human visual perception system is complex, it is challenging to produce AR technology that facilitates a comfortable, natural-feeling, rich presentation of virtual image elements amongst other virtual or real-world imagery elements.

Systems and methods disclosed herein address various challenges related to AR and VR technology.

SUMMARY

In some embodiments, an optical system comprises an optically transmissive substrate comprising a metasurface

which comprises a grating comprising a plurality of unit cells. Each unit cell comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width. The heights of the first and the second nanobeams are: 10 nm to 450 nm where a refractive index of the substrate is more than 3.3; and 10 nm to 1 μ m where the refractive index is 3.3 or less.

In some other embodiments, an optical system comprises an optically transmissive substrate comprising a metasurface which comprises a grating comprising a plurality of unit cells. Each unit cell comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap. The second nanobeam has a second width larger than the first width. The optical system also comprises a reflector. The reflector and the substrate are on opposite sides of the grating.

In yet other embodiments, a method for forming a metasurface comprises providing an optically transmissive substrate; providing an optically transmissive layer over the substrate; and patterning the optically transmissive layer to define a grating comprising a plurality of unit cells. Each unit cell comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width. The heights of the first and the second nanobeams are: 10 nm to 450 nm where a refractive index of the substrate is more than 3.3; and 10 nm to 1 μ m where the refractive index is 3.3 or less.

In some other embodiments, a method for forming a metasurface comprises providing an optically transmissive substrate and forming a grating comprising a plurality of unit cells. Each unit cell comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width. The method also comprises providing a layer of reflective material in the gap and between the unit cells.

In some other embodiments, a method for forming a metasurface comprises providing an optically transmissive substrate; and forming a grating comprising a plurality of unit cells. Each unit cell comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width. The method further comprises depositing a layer of optically transmissive spacer material in the gap and between the unit cells; and depositing a reflective layer on the layer of spacer material, wherein the spacer material separates the grating from the reflective layer.

In yet other embodiments, an optical system comprises an optically transmissive substrate comprising a metasurface which comprises a grating comprising a plurality of unit cells. Each unit cell comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width. A pitch of the unit cells is 10 nm to 1 μ m.

In some other embodiments, a method for forming a metasurface comprises providing an optically transmissive substrate; providing an optically transmissive layer over the substrate; and patterning the optically transmissive layer to define a grating comprising a plurality of unit cells. Each

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unit cell comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width. A pitch of the unit cells is 10 nm to 1 μ m.

In yet other embodiments, an optical system comprises an optically transmissive substrate comprising a multilevel metasurface. The multilevel metasurface comprises a grating comprising a plurality of multilevel unit cells. Each unit cell comprises, on a lowermost level of the unit cell, a laterally-elongated, first lowermost level nanobeam having a first width; and a laterally-elongated, second lowermost level nanobeam having a second width, where the second width is larger than the first width. On an uppermost level of the unit cell is a laterally-elongated, first uppermost level nanobeam above the first lowermost level nanobeam; and a laterally-elongated, second uppermost level nanobeam above the second lowermost level nanobeam.

In some other embodiments, a method for forming a metasurface comprises providing an optically transmissive substrate; providing an optically transmissive layer over the substrate; and patterning the optically transmissive layer to define a plurality of repeating units. Each repeating unit comprises a laterally-elongated first nanobeam having a first width; and a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width. The method also comprises depositing an optically transmissive material on the first and second nanobeams and into the gaps between the nanobeams to form spaced apart plateaus of the optically transmissive material above the nanobeams.

Additional example embodiments are provided below.

1. An optical system comprising:

an optically transmissive substrate comprising a metasurface, the metasurface comprising, as seen in a top-down view:

a grating comprising a plurality of unit cells, each unit cell comprising:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width,

wherein heights of the first and the second nanobeams are:

10 nm to 450 nm where a refractive index of the substrate is more than 3.3; and

10 nm to 1 μ m where the refractive index is 3.3 or less.

2. The optical system of embodiment 1, wherein the unit cells are laterally-elongated and are parallel to each other.

3. The optical system of embodiment 1, wherein the metasurface is configured to diffract incident light of a visible wavelength into a first diffraction order.

4. The optical system of embodiment 1, wherein the second width is 10 nm to 1 μ m.

5. The optical system of embodiment 4, wherein the second width is 10 nm to 300 nm.

6. The optical system of embodiment 1, wherein a pitch of the unit cells is 10 nm to 1 μ m.

7. The optical system of embodiment 6, wherein the pitch of the unit cells is 10 nm to 500 nm.

8. The optical system of embodiment 1, wherein the first nanobeam and the second nanobeam are separated by a gap of 10 nm to 1 μ m.

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9. The optical system of embodiment 8, wherein the gap is 10 nm to 300 nm wide.

10. The optical system of embodiment 1, wherein the optically transmissive substrate comprises a glass.

11. The optical system of embodiment 1, wherein the first and second nanobeam comprises silicon.

12. The optical system of embodiment 11, wherein the first and second nanobeam comprises silicon nitride.

13. The optical system of embodiment 1, wherein the optically transmissive substrate and the metasurface form a polarizing beam splitter.

14. The optical system of embodiment 1, wherein the optically transmissive substrate is a waveguide plate.

15. The optical system of embodiment 14, further comprising a stack of the optically transmissive substrates, wherein dimensions of features of the unit cells varies between the substrates.

16. The optical system of embodiment 1, wherein the metasurface is an incoupling optical element, further comprising an image injection device configured to project light to the incoupling optical element, wherein the metasurface is configured to redirect the light to propagate the light through the substrate by total internal reflection.

17. The optical system of embodiment 1, wherein the metasurface is an outcoupling optical element, wherein the metasurface is configured to extract light out of the substrate.

18. An optical system comprising:

an optically transmissive substrate comprising a metasurface, the metasurface comprising:

a grating comprising a plurality of unit cells, each unit cell comprising, as seen in a top-down view:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width; and

a reflector, wherein the reflector and the substrate are on opposite sides of the grating.

19. The optical system of embodiment 18, wherein the reflector is spaced apart from the grating.

20. The optical system of embodiment 19, wherein the grating is embedded in an optically transmissive material.

21. The optical system of embodiment 20, wherein the optically transmissive material spaces the reflector apart from the grating.

22. The optical system of embodiment 18, wherein the substrate comprises:

a second metasurface on a side of the substrate opposite the metasurface, the second metasurface comprising:

a second grating comprising a plurality of second unit cells, each second unit cell comprising, as seen in a top-down view:

a laterally-elongated third nanobeam; and

a laterally-elongated fourth nanobeam spaced apart from the third nanobeam by a gap, wherein the fourth nanobeam is wider than the third nanobeam.

23. The optical system of embodiment 18, wherein the unit cells are laterally-elongated and are parallel to each other.

24. The optical system of embodiment 18, wherein the metasurface is configured to diffract incident light of a visible wavelength into a first diffraction order

25. The optical system of embodiment 18, wherein the second width is 10 nm to 1 μ m. will

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26. The optical system of embodiment 25, wherein the second width is 10 nm to 300 nm.

27. The optical system of embodiment 18, wherein a pitch of the unit cells is 10 nm to 1 μ m.

28. The optical system of embodiment 27, wherein the pitch of the unit cells is 10 nm to 500 nm.

29. The optical system of embodiment 18, wherein the first nanobeam and the second nanobeam are separated by a gap of 10 nm to 1 μ m.

30. The optical system of embodiment 29, wherein the gap is 10 nm to 300 nm wide.

31. The optical system of embodiment 18, wherein the optically transmissive substrate comprises a glass.

32. The optical system of embodiment 18, wherein the first and second nanobeam comprises silicon.

33. The optical system of embodiment 32, wherein the first and second nanobeam comprises silicon nitride.

34. The optical system of embodiment 18, wherein the optically transmissive substrate and the metasurface form a polarizing beam splitter.

35. The optical system of embodiment 27, wherein the optically transmissive substrate is a waveguide plate.

36. The optical system of embodiment 35, further comprising a stack of the optically transmissive substrates, wherein dimensions of features of the unit cells varies between the substrates.

37. The optical system of embodiment 18, wherein the metasurface is an incoupling optical element, further comprising an image injection device configured to project light to the incoupling optical element, wherein the metasurface is configured to redirect the light to propagate the light through the substrate by total internal reflection.

38. The optical system of embodiment 18, wherein the metasurface is an outcoupling optical element, wherein the metasurface is configured to extract light out of the substrate.

39. A method for forming a metasurface, the method comprising:

providing an optically transmissive substrate;
providing an optically transmissive layer over the substrate; and

patterning the optically transmissive layer to define a grating comprising a plurality of unit cells, each unit cell comprising, as seen in a top-down view:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width,

wherein heights of the first and the second nanobeams are:

10 nm to 450 nm where a refractive index of the substrate is more than 3.3; and

10 nm to 1 μ m where the refractive index is 3.3 or less.

40. The method of embodiment 39, wherein patterning the optically transmissive layer comprises:

providing a resist layer over the optically transmissive layer;

defining a pattern in the resist layer; and

transferring the pattern from the resist layer to the optically transmissive layer.

41. The method of embodiment 40, further comprising depositing an optically transmissive material between and over the grating.

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42. The method of embodiment 41, further comprising forming a reflective layer on the optically transmissive material.

43. The method of embodiment 40, wherein transferring comprises performing an anisotropic etch.

44. A method for forming a metasurface, the method comprising:

providing an optically transmissive substrate;

forming a grating comprising a plurality of unit cells, each unit cell comprising, as seen in a top-down view:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width, and providing a layer of reflective material in the gap and between the unit cells.

45. The method of embodiment 44, wherein providing the layer of reflective material comprises depositing reflective material between and over the first and second nanobeams.

46. The method of embodiment 45, wherein the reflective material comprises aluminum.

47. The method of embodiment 44, wherein forming the grating comprises:

depositing an optically transmissive layer over the substrate; and

patterning the optically transmissive layer to define the grating.

48. The method of embodiment 47, wherein patterning the optically transmissive layer comprises:

providing a resist layer over the optically transmissive layer;

defining a pattern in the resist layer; and

transferring the pattern from the resist layer to the optically transmissive layer.

49. A method for forming a metasurface, the method comprising:

providing an optically transmissive substrate;

forming a grating comprising a plurality of unit cells, each unit cell comprising, as seen in a top-down view:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width,

depositing a layer of optically transmissive spacer material in the gap and between the unit cells; and

depositing a reflective layer on the layer of spacer material, wherein the spacer material separates the grating from the reflective layer.

50. The method of embodiment 49, wherein the spacer material has a refractive index of 1 to 2.

51. An optical system comprising:

an optically transmissive substrate comprising a metasurface, the metasurface comprising:

a grating comprising a plurality of unit cells, each unit cell comprising, as seen in a top-down view:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width,

wherein a pitch of the unit cells is 10 nm to 1 μ m.

52. The system of embodiment 51, wherein the pitch is 300 nm to 500 nm.

53. The system of embodiment 51, wherein the metasurface is configured to diffract incident light of a visible wavelength into a first diffraction order.

54. The optical system of embodiment 51, wherein the unit cells are laterally-elongated and are parallel to each other.

55. The optical system of embodiment 51, wherein the second width is 10 nm to 1 μ m.

56. The optical system of embodiment 55, wherein the second width is 10 nm to 300 nm.

57. The optical system of embodiment 51, wherein a pitch of the unit cells is 10 nm to 1 μ m.

58. The optical system of embodiment 57, wherein the pitch of the unit cells is 10 nm to 500 nm.

59. The optical system of embodiment 51, wherein the first nanobeam and the second nanobeam are separated by a gap of 10 nm to 1 μ m.

60. The optical system of embodiment 59, wherein the gap is 10 nm to 300 nm wide.

61. The optical system of embodiment 51, wherein the optically transmissive substrate comprises a glass.

62. The optical system of embodiment 51, wherein the first and second nanobeam comprises silicon.

63. The optical system of embodiment 62, wherein the first and second nanobeam comprises silicon nitride.

64. The optical system of embodiment 51, wherein the optically transmissive substrate and the metasurface form a polarizing beam splitter.

65. The optical system of embodiment 51, wherein the optically transmissive substrate is a waveguide plate.

66. The optical system of embodiment 65, further comprising a stack of the optically transmissive substrates, wherein dimensions of features of the unit cells varies between the substrates.

67. The optical system of embodiment 51, wherein the metasurface is an incoupling optical element, further comprising an image injection device configured to project light to the incoupling optical element, wherein the metasurface is configured to redirect the light to propagate the light through the substrate by total internal reflection.

68. The optical system of embodiment 51, wherein the metasurface is an outcoupling optical element, wherein the metasurface is configured to extract light out of the substrate.

69. A method for forming a metasurface, the method comprising:

providing an optically transmissive substrate;

providing an optically transmissive layer over the substrate; and

patterning the optically transmissive layer to define a grating comprising a plurality of unit cells, each unit cell comprising, as seen in a top-down view:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width,

wherein a pitch of the unit cells is 10 nm to 1 μ m.

70. The method of embodiment 69, wherein the metasurface is configured to diffract incident light of a visible wavelength into a first diffraction order.

71. An optical system comprising:

an optically transmissive substrate comprising a multilevel metasurface, the multilevel metasurface comprising:

a grating comprising a plurality of multilevel unit cells, each unit cell comprising, as seen in a top-down view:

on a lowermost level of the unit cell:

a laterally-elongated, first lowermost level nanobeam having a first width; and

a laterally-elongated, second lowermost level nanobeam having a second width, wherein the second width is larger than the first width; and

on an uppermost level of the unit cell:

a laterally-elongated, first uppermost level nanobeam above the first lowermost level nanobeam; and

a laterally-elongated, second uppermost level nanobeam above the second lowermost level nanobeam.

72. The optical system of embodiment 71, wherein the first and second uppermost level nanobeams comprise a different material from the first and second lowermost level nanobeams.

73. The optical system of embodiment 71, wherein the first and second lowermost level nanobeams comprise photoresist.

74. The optical system of embodiment 73, wherein the first and second lowermost level nanobeams comprise silicon.

75. The optical system of embodiment 74, wherein the first and second lowermost level nanobeams comprise silicon nitride.

76. The optical system of embodiment 73, wherein the first and second lowermost level nanobeams comprise an oxide.

77. The optical system of embodiment 76, wherein the first and second lowermost level nanobeams comprise titanium oxide.

78. The optical system of embodiment 71, wherein the first and second lowermost level nanobeams of the plurality of unit cells extend parallel to each other.

79. The optical system of embodiment 71, wherein the first width is 10 nm to 250 nm.

80. The optical system of embodiment 79, wherein the second width is 10 nm to 300 nm.

81. The optical system of embodiment 71, wherein a pitch of the unit cells is 300 nm to 500 nm.

82. The optical system of embodiment 71, wherein the first nanobeam and the second nanobeam are separated by a gap of 10 nm to 300 nm.

83. The optical system of embodiment 71, wherein the optically transmissive substrate and the metasurface form a polarizing beam splitter.

84. The optical system of embodiment 71, wherein the optically transmissive substrate is a waveguide plate.

85. The optical system of embodiment 71, wherein the metasurface forms an incoupling optical element, further comprising an image injection device configured to project light to the incoupling optical element, wherein the metasurface is configured to redirect the light to propagate the light through the substrate by total internal reflection.

86. The optical system of embodiment 84, further comprising a stack of the optically transmissive substrates, wherein dimensions of features of the unit cells varies between the substrates, wherein the metasurface is an incoupling optical element, further comprising an image injection device configured to project light to the incoupling optical

element, wherein the metasurface is configured to redirect the light to propagate the light through the substrate by total internal reflection.

87. The optical system of embodiment 71, wherein the metasurface is an outcoupling optical element, wherein the metasurface is configured to extract light out of the substrate.

88. The optical system of embodiment 71, wherein the grating is embedded in an optically transmissive material.

89. A method for forming a metasurface, the method comprising:

providing an optically transmissive substrate;
providing an optically transmissive layer over the substrate; and

patterning the optically transmissive layer to define a plurality of repeating units, each repeating unit comprising, as seen in a top-down view:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced-apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width; and

depositing an optically transmissive material on the first and second nanobeams and into the gaps between the nanobeams to form spaced apart plateaus of the optically transmissive material above the nanobeams.

90. The method of embodiment 89, wherein the optically transmissive material has a higher refractive index than either the patterned resist or the substrate.

91. The method of embodiment 89, wherein patterning the optically transmissive layer comprises patterning resist.

92. The method of embodiment 91, wherein patterning the resist comprises imprinting the pattern into the resist.

93. The method of embodiment 91, wherein depositing the optically transmissive material comprises spin coating the optically transmissive material on the patterned resist.

94. The method of embodiment 91, wherein depositing the optically transmissive material comprises performing a conformal deposition or a directional deposition of the optically transmissive material.

95. The method of embodiment 94, wherein the conformal deposition comprises chemical vapor deposition or atomic layer deposition of the optically transmissive material.

96. The method of embodiment 95, wherein the directional deposition comprises evaporation or sputtering the optically transmissive material.

97. The method of embodiment 89, wherein the first width is 10 nm to 250 nm.

98. The method of embodiment 97, wherein the second width is 10 nm to 300 nm.

99. The method of embodiment 89, wherein a pitch of the unit cells is 300 nm to 500 nm.

100. The optical system of embodiment 89, wherein the first nanobeam and the second nanobeam are separated by a gap of 10 nm to 300 nm.

101. The method of embodiment 89, wherein the optically transmissive substrate is a waveguide.

Additional and other objects, features, and advantages of the invention are described in the detail description, figures and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a user's view of augmented reality (AR) through an AR device.

FIG. 2 illustrates a conventional display system for simulating three-dimensional imagery for a user.

FIGS. 3A-3C illustrate relationships between radius of curvature and focal radius.

FIG. 4A illustrates a representation of the accommodation-vergence response of the human visual system.

FIG. 4B illustrates examples of different accommodative states and vergence states of a pair of eyes of the user.

FIG. 4C illustrates an example of a representation of a top-down view of a user viewing content via a display system.

FIG. 4D illustrates another example of a representation of a top-down view of a user viewing content via a display system.

FIG. 5 illustrates aspects of an approach for simulating three-dimensional imagery by modifying wavefront divergence.

FIG. 6 illustrates an example of a waveguide stack for outputting image information to a user.

FIG. 7 illustrates an example of exit beams outputted by a waveguide.

FIG. 8 illustrates an example of a stacked waveguide assembly in which each depth plane includes images formed using multiple different component colors.

FIG. 9A illustrates a cross-sectional side view of an example of a set of stacked waveguides that each includes an incoupling optical element.

FIG. 9B illustrates a perspective view of an example of the plurality of stacked waveguides of FIG. 9A.

FIG. 9C illustrates a top-down plan view of an example of the plurality of stacked waveguides of FIGS. 9A and 9B.

FIG. 9D illustrates an example of wearable display system.

FIGS. 10A and 10B illustrate examples of cross-sectional side and top-down views, respectively, of a metasurface.

FIG. 11A illustrates an example of a cross-sectional side view of a metasurface configured to function in a reflective mode.

FIG. 11B illustrates an example of a cross-sectional, top-down view of the metasurface of FIG. 11A as viewed on the plane 11B of FIG. 11A.

FIG. 12 illustrates an example of a cross-sectional side view of another metasurface configured to function in a reflective mode.

FIG. 13 illustrates an example of a cross-sectional, top-down view of the metasurface of FIG. 12 as viewed on the plane 13 of FIG. 12.

FIG. 14A illustrates an example of a cross-sectional side view of a substrate having both transmissive and reflective metasurface.

FIG. 14B illustrates an example of a top-down view of the metasurface of FIG. 14A.

FIG. 14C illustrates an example of a top-down view of the metasurface of FIG. 14A viewed on the plane 14C of FIG. 14A.

FIGS. 15A-15E illustrate an example of a process flow for forming a metasurface.

FIGS. 16A and 16B illustrate scanning electron micrographs of a metasurface.

FIG. 17 illustrates an example of a plot showing the diffraction efficiency versus angle of incidence of light for a transmissive metasurface.

FIGS. 18A-18C illustrate examples of plots showing the diffraction efficiency versus angle of incidence of light for a reflective metasurface. The wavelengths of incident light are different for each of FIGS. 18A-18C.

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FIGS. 19A and 19B illustrate examples of plots showing the polarization sensitivity of the metasurface of FIGS. 10A and 10B.

FIG. 20 illustrates plots of amplitude and phase shift versus nanobeam width for the metasurface of FIGS. 10A and 10B.

FIG. 21A illustrates an example of a cross-sectional side view of a multilevel metasurface.

FIG. 21B illustrates an example of a plot of transmission and reflection as a function of the angle of incidence of light for an optical structure having the general structure shown in FIG. 21A.

FIG. 22A illustrates an example of a cross-sectional side view of a multilevel metasurface.

FIG. 22B illustrates an example of a plot of transmission and reflection as a function of the angle of incidence of light for an optical structure having the general structure shown in FIG. 22A.

FIGS. 23A-23D illustrate an example of a process flow for forming multilevel metasurfaces.

The drawings are provided to illustrate example embodiments described herein and are not intended to limit the scope of the disclosure. It will be appreciated that the drawings are schematic and not necessarily drawn to scale.

DETAILED DESCRIPTION

Metasurfaces, metamaterial surfaces, provide opportunities to realize virtually flat, aberration-free optics on much smaller scales, in comparison with geometrical optics. Without being limited by theory, in some embodiments, metasurfaces include dense arrangements of surface structures that function as resonant optical antennas. The resonant nature of the light-surface structure interaction provides the ability to manipulate optical wave-fronts. In some cases, the metasurfaces may allow the replacement of bulky or difficult to manufacture optical components with thin, planar elements formed by simple patterning processes.

One type of a conventional optical element is a blaze grating, which may be desirable in some applications for having high selectivity in redirecting light. These gratings, however, typically have sloped surfaces and may be challenging to manufacture. Advantageously, in some embodiments, metasurfaces are disclosed that are able to redirect light, similar to a blazed grating, in the visible range while having a relatively flat response over a wide range of incoming angles, and while providing a more easily manufactured structure.

The metasurfaces may take the form of an asymmetric grating formed by a plurality of repeating unit cells. Each unit cell comprises two laterally-elongated protrusions, which may be also referred to as nanobeams or nanowires, with one protrusion being wider than the other. As used herein, a protrusion, nanobeam or nanowire, is an elongated volume of material, e.g., a single substantially homogeneous material. It will be appreciated that these elongated structures are not limited to any particular cross-sectional shape. In some embodiments, the cross-sectional shape is rectangular. Preferably, the nanobeams have a sub-wavelength width and spacing from one another. For example, the widths of the nanobeams may be less than the wavelengths of light that the metasurface is configured to redirect. In some embodiments, the units cells formed by the nanobeams may be on or proximate the surface of an optically transmissive substrate, e.g., a waveguide.

In some embodiments, the metasurfaces may work in a transmission mode in which light is incident on the meta-

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surface from a first side of the metasurface, propagates through the metasurface, and subsequently propagates away from the metasurface on an opposite side of the metasurface. The light propagates away from the metasurface in a direction different from the incident direction of the light on the first side.

In some other embodiments, the metasurface may work in a reflective mode in which the light is incident from the first side of the metasurface, and is reflected back on the first side to propagate away from the metasurface. In the reflective mode, the metasurface may include nanobeams embedded within a reflective layer. In some other embodiments, the nanobeams may be embedded within a spacer layer, and a reflective layer may be provided directly on the spacer layer, on a side of the metasurface opposite the first side.

Preferably, the features forming the metasurface are configured to redirect light, e.g. by diffraction. In some embodiments, the light is visible light having a wavelength in the range of 350 nm to 800 nm. In some embodiments, the metasurface is configured to diffract incident light of a visible wavelength into a first diffraction order

In some embodiments, the widths of the nanobeams forming the unit cells are in the range of 10 nm to 1 μ m, including 10 nm to 300 nm or 10 nm to 250 nm. The nanobeams may be separated by a gap in the range of 5 nm to 1 μ m wide, including 10 nm to 1 μ m wide or 10 nm to 300 nm wide. The pitch of the unit cells (that is, the distance between identical points in directly neighboring unit cells) may be in the range of 10 nm to 1 μ m, including 10 nm to 500 nm, or 300 nm to 500 nm. In some embodiments, the heights of the nanobeams may be in the range of 10 nm to 1 μ m, including 10 nm to 500 nm or 10 nm to 450 nm.

It has been found that the dimensions of features of the unit cells may vary depending upon the properties of the materials used to form the metasurface. For example, the height of the nanobeams may vary depending upon the refractive index of the material used for those nanobeams. In some embodiments, the heights of the nanobeams may be 10 nm to 450 nm where a refractive index of the material is more than 3.3; and 10 nm to 1 μ m where the refractive index is 3.3 or less. As another example, the height of the nanobeams may be 10 nm to 450 nm where the nanobeams are formed of silicon (e.g., amorphous or polysilicon).

In some embodiments, the metasurface is a multilevel (e.g., bi-level) structure having unit cells with relatively narrow and relatively wide nanobeams as noted above on a lowermost level, and a second optically transmissive material between the nanobeams on the lowermost level. The metasurface may also include a second level formed by a second optically transmissive material disposed on top surfaces of the nanobeams. The material on the second level may be localized on the top surfaces of the nanobeams and may form spaced apart plateaus of the material, as seen in a cross-sectional view taken along a plane orthogonal to the length axis of the nanobeams. In some embodiments, the heights of the material on the second level may be in the range of 10 nm to 1 μ m, including 10 nm to 600 nm.

It will be appreciated that, in some embodiments, the metasurface selectively redirects some wavelengths of light, while being transmissive to other wavelengths of light. Such properties are typically engineered with structures on micron scales (e.g., in photonics crystal fibers or distributed bragg reflectors), while various embodiments herein include geometries on nano-scales (e.g. 10-100 $\times$ smaller scales), and provide selective redirection of light in the visible part of the electromagnetic spectrum. In some embodiments, the nanobeams may be formed on the surface of the substrate a single

level, thereby providing a simple to manufacture structure. Advantageously, the metasurfaces may be formed using patterning and deposition processes, e.g., lithography and chemical etching. In some embodiments, the metasurfaces may be patterned using nanoimprinting, thereby avoiding costly lithography and etch processes.

Metasurfaces formed according to various embodiments provide one or more of the following advantages. For example, the metasurfaces may have a relatively large angular bandwidth over which it may redirect or diffract light. In addition, the metasurfaces may have a good diffraction efficiency over this bandwidth. For example, the diffraction efficiency may be 25% or more, 30% or more, or 40% or more, over an angular bandwidth (FWHM) of 40°, or 50° (as measured from the normal to a surface). Moreover, the diffraction efficiency over the angular bandwidth may be advantageously flat, e.g., varying by less than 25%, 20%, 15%, or 10% over the angular bandwidth. The metasurfaces may also have a large deflection angle, which may advantageously be applied to incouple light within the angular bandwidth by redirecting the light such that it propagates at angles suitable for total internal reflection (TIR). In addition, the advantages noted above may be realized in a number of wavelengths of light corresponding to different component colors for forming images. For example, the wavelengths may correspond to the colors red, green, and blue (e.g. wavelengths of 455 nm, 520 nm, and 638 nm). In a reflective mode, the metasurface may provide color selective beam shaping with a high extinction ratio (e.g., 5 or more, 10 or more, 20 or more). In some embodiments, the metasurfaces exhibit strong polarization dependence and may function as a polarization beam splitter. For example, for light of different polarizations, the metasurface may exhibit extinction ratios of 5 or more, 7 or more, or 9 or more.

In some embodiments, the waveguides supporting the metasurfaces may form direct view display devices or near-eye display devices, with the waveguides configured to receive input image information and generate an output image based on the input image information. These devices may be wearable and constitute eyewear in some embodiments. The input image information received by the waveguides can be encoded in multiplexed light streams of different wavelengths (e.g., red, green and blue light) that are incoupled into one or more waveguides. Incoupled light may propagate through the waveguide due to total internal reflection. The incoupled light may be outcoupled (or outputted) from the waveguide by one or more outcoupling optical elements.

In some embodiments, the metasurfaces be the incoupling and/or outcoupling optical elements. The compactness and planarity of the metasurface allows for a compact waveguide, and for a compact stack of waveguides where multiple waveguides form a stack. In addition, the high wavelength selectivity of the metasurface allows for a high degree of precision in incoupling and/or outcoupling light, which can provide high image quality in applications where the light contains image information. For example, the high selectivity may reduce channel crosstalk in configurations in which full color images are formed by outputting light of different colors or wavelengths at the same time.

Reference will now be made to the Figures, in which like reference numbers refer to like features throughout.

Example Display Systems

Various embodiments disclosed herein may be implemented in optical devices to steer or redirect light, and may be particularly advantageously employed as parts of display

systems. In some embodiments, the display systems take the form of eyewear (e.g., they are wearable), which may advantageously provide a highly immersive VR or AR experience. For example, displays containing waveguides for displaying multiple depth planes, e.g. a stack of waveguides (one waveguide or set of waveguides for each depth plane), may be configured to be worn positioned in front of the eyes of a user, or viewer. In some embodiments, multiple waveguides, e.g. two stacks of waveguides, one for each eye of a viewer, may be utilized to provide different images to each eye.

FIG. 2 illustrates a conventional display system for simulating three-dimensional imagery for a user. It will be appreciated that a user's eyes are spaced apart and that, when looking at a real object in space, each eye will have a slightly different view of the object and may form an image of the object at different locations on the retina of each eye. This may be referred to as binocular disparity and may be utilized by the human visual system to provide a perception of depth. Conventional display systems simulate binocular disparity by presenting two distinct images **190**, **200** with slightly different views of the same virtual object—one for each eye **210**, **220**—corresponding to the views of the virtual object that would be seen by each eye were the virtual object a real object at a desired depth. These images provide binocular cues that the user's visual system may interpret to derive a perception of depth.

With continued reference to FIG. 2, the images **190**, **200** are spaced from the eyes **210**, **220** by a distance **230** on a z-axis. The z-axis is parallel to the optical axis of the viewer with their eyes fixated on an object at optical infinity directly ahead of the viewer. The images **190**, **200** are flat and at a fixed distance from the eyes **210**, **220**. Based on the slightly different views of a virtual object in the images presented to the eyes **210**, **220**, respectively, the eyes may naturally rotate such that an image of the object falls on corresponding points on the retinas of each of the eyes, to maintain single binocular vision. This rotation may cause the lines of sight of each of the eyes **210**, **220** to converge onto a point in space at which the virtual object is perceived to be present. As a result, providing three-dimensional imagery conventionally involves providing binocular cues that may manipulate the vergence of the user's eyes **210**, **220**, and that the human visual system interprets to provide a perception of depth.

Generating a realistic and comfortable perception of depth is challenging, however. It will be appreciated that light from objects at different distances from the eyes have wavefronts with different amounts of divergence. FIGS. 3A-3C illustrate relationships between distance and the divergence of light rays. The distance between the object and the eye **210** is represented by, in order of decreasing distance, **R1**, **R2**, and **R3**. As shown in FIGS. 3A-3C, the light rays become more divergent as distance to the object decreases. Conversely, as distance increases, the light rays become more collimated. Stated another way, it may be said that the light field produced by a point (the object or a part of the object) has a spherical wavefront curvature, which is a function of how far away the point is from the eye of the user. The curvature increases with decreasing distance between the object and the eye **210**. While only a single eye **210** is illustrated for clarity of illustration in FIGS. 3A-3C and other figures herein, the discussions regarding eye **210** may be applied to both eyes **210** and **220** of a viewer.

With continued reference to FIGS. 3A-3C, light from an object that the viewer's eyes are fixated on may have different degrees of wavefront divergence. Due to the dif-

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ferent amounts of wavefront divergence, the light may be focused differently by the lens of the eye, which in turn may require the lens to assume different shapes to form a focused image on the retina of the eye. Where a focused image is not formed on the retina, the resulting retinal blur acts as a cue to accommodation that causes a change in the shape of the lens of the eye until a focused image is formed on the retina. For example, the cue to accommodation may trigger the ciliary muscles surrounding the lens of the eye to relax or contract, thereby modulating the force applied to the suspensory ligaments holding the lens, thus causing the shape of the lens of the eye to change until retinal blur is eliminated or minimized, thereby forming a focused image of the object of fixation on the retina/fovea of the eye. The process by which the lens of the eye changes shape may be referred to as accommodation, and the shape of the lens of the eye required to form a focused image of the object of fixation on the retina/fovea of the eye may be referred to as an accommodative state.

With reference now to FIG. 4A, a representation of the accommodation-vergence response of the human visual system is illustrated. The movement of the eyes to fixate on an object causes the eyes to receive light from the object, with the light forming an image on each of the retinas of the eyes. The presence of retinal blur in the image formed on the retina may provide a cue to accommodation, and the relative locations of the image on the retinas may provide a cue to vergence. The cue to accommodation causes accommodation to occur, resulting in the lenses of the eyes each assuming a particular accommodative state that forms a focused image of the object on the retina/fovea of the eye. On the other hand, the cue to vergence causes vergence movements (rotation of the eyes) to occur such that the images formed on each retina of each eye are at corresponding retinal points that maintain single binocular vision. In these positions, the eyes may be said to have assumed a particular vergence state. With continued reference to FIG. 4A, accommodation may be understood to be the process by which the eye achieves a particular accommodative state, and vergence may be understood to be the process by which the eye achieves a particular vergence state. As indicated in FIG. 4A, the accommodative and vergence states of the eyes may change if the user fixates on another object. For example, the accommodated state may change if the user fixates on a new object at a different depth on the z-axis.

Without being limited by theory, it is believed that viewers of an object may perceive the object as being “three-dimensional” due to a combination of vergence and accommodation. As noted above, vergence movements (e.g., rotation of the eyes so that the pupils move toward or away from each other to converge the lines of sight of the eyes to fixate upon an object) of the two eyes relative to each other are closely associated with accommodation of the lenses of the eyes. Under normal conditions, changing the shapes of the lenses of the eyes to change focus from one object to another object at a different distance will automatically cause a matching change in vergence to the same distance, under a relationship known as the “accommodation-vergence reflex.” Likewise, a change in vergence will trigger a matching change in lens shape under normal conditions.

With reference now to FIG. 4B, examples of different accommodative and vergence states of the eyes are illustrated. The pair of eyes **222a** are fixated on an object at optical infinity, while the pair eyes **222b** are fixated on an object **221** at less than optical infinity. Notably, the vergence states of each pair of eyes is different, with the pair of eyes **222a** directed straight ahead, while the pair of eyes **222**

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converge on the object **221**. The accommodative states of the eyes forming each pair of eyes **222a** and **222b** are also different, as represented by the different shapes of the lenses **210a**, **220a**.

Undesirably, many users of conventional “3-D” display systems find such conventional systems to be uncomfortable or may not perceive a sense of depth at all due to a mismatch between accommodative and vergence states in these displays. As noted above, many stereoscopic or “3-D” display systems display a scene by providing slightly different images to each eye. Such systems are uncomfortable for many viewers, since they, among other things, simply provide different presentations of a scene and cause changes in the vergence states of the eyes, but without a corresponding change in the accommodative states of those eyes. Rather, the images are shown by a display at a fixed distance from the eyes, such that the eyes view all the image information at a single accommodative state. Such an arrangement works against the “accommodation-vergence reflex” by causing changes in the vergence state without a matching change in the accommodative state. This mismatch is believed to cause viewer discomfort. Display systems that provide a better match between accommodation and vergence may form more realistic and comfortable simulations of three-dimensional imagery.

Without being limited by theory, it is believed that the human eye typically may interpret a finite number of depth planes to provide depth perception. Consequently, a highly believable simulation of perceived depth may be achieved by providing, to the eye, different presentations of an image corresponding to each of these limited numbers of depth planes. In some embodiments, the different presentations may provide both cues to vergence and matching cues to accommodation, thereby providing physiologically correct accommodation-vergence matching.

With continued reference to FIG. 4B, two depth planes **240**, corresponding to different distances in space from the eyes **210**, **220**, are illustrated. For a given depth plane **240**, vergence cues may be provided by the displaying of images of appropriately different perspectives for each eye **210**, **220**. In addition, for a given depth plane **240**, light forming the images provided to each eye **210**, **220** may have a wavefront divergence corresponding to a light field produced by a point at the distance of that depth plane **240**.

In the illustrated embodiment, the distance, along the z-axis, of the depth plane **240** containing the point **221** is 1 m. As used herein, distances or depths along the z-axis may be measured with a zero point located at the exit pupils of the user’s eyes. Thus, a depth plane **240** located at a depth of 1 m corresponds to a distance of 1 m away from the exit pupils of the user’s eyes, on the optical axis of those eyes. As an approximation, the depth or distance along the z-axis may be measured from the display in front of the user’s eyes (e.g., from the surface of a waveguide), plus a value for the distance between the device and the exit pupils of the user’s eyes. That value may be called the eye relief and corresponds to the distance between the exit pupil of the user’s eye and the display worn by the user in front of the eye. In practice, the value for the eye relief may be a normalized value used generally for all viewers. For example, the eye relief may be assumed to be 20 mm and a depth plane that is at a depth of 1 m may be at a distance of 980 mm in front of the display.

With reference now to FIGS. 4C and 4D, examples of matched accommodation-vergence distances and mismatched accommodation-vergence distances are illustrated, respectively. As illustrated in FIG. 4C, the display system

may provide images of a virtual object to each eye **210, 220**. The images may cause the eyes **210, 220** to assume a vergence state in which the eyes converge on a point **15** on a depth plane **240**. In addition, the images may be formed by a light having a wavefront curvature corresponding to real objects at that depth plane **240**. As a result, the eyes **210, 220** assume an accommodative state in which the images are in focus on the retinas of those eyes. Thus, the user may perceive the virtual object as being at the point **15** on the depth plane **240**.

It will be appreciated that each of the accommodative and vergence states of the eyes **210, 220** are associated with a particular distance on the z-axis. For example, an object at a particular distance from the eyes **210, 220** causes those eyes to assume particular accommodative states based upon the distances of the object. The distance associated with a particular accommodative state may be referred to as the accommodation distance, A_d . Similarly, there are particular vergence distances, V_d , associated with the eyes in particular vergence states, or positions relative to one another. Where the accommodation distance and the vergence distance match, the relationship between accommodation and vergence may be said to be physiologically correct. This is considered to be the most comfortable scenario for a viewer.

In stereoscopic displays, however, the accommodation distance and the vergence distance may not always match. For example, as illustrated in FIG. 4D, images displayed to the eyes **210, 220** may be displayed with wavefront divergence corresponding to depth plane **240**, and the eyes **210, 220** may assume a particular accommodative state in which the points **15a, 15b** on that depth plane are in focus. However, the images displayed to the eyes **210, 220** may provide cues for vergence that cause the eyes **210, 220** to converge on a point **15** that is not located on the depth plane **240**. As a result, the accommodation distance corresponds to the distance from the exit pupils of the eyes **210, 220** to the depth plane **240**, while the vergence distance corresponds to the larger distance from the exit pupils of the eyes **210, 220** to the point **15**, in some embodiments. The accommodation distance is different from the vergence distance. Consequently, there is an accommodation-vergence mismatch. Such a mismatch is considered undesirable and may cause discomfort in the user. It will be appreciated that the mismatch corresponds to distance (e.g., $V_d - A_d$) and may be characterized using diopters.

Without being limited by theory, it is believed that users may still perceive accommodation-vergence mismatches of up to 0.25 diopter, up to 0.33 diopter, and up to about 0.5 diopter as being physiologically correct, without the mismatch itself causing significant discomfort. In some embodiments, display systems disclosed herein (e.g., the display system **250**, FIG. 6) are configured to present images to the viewer using light with wavefront divergence and images with binocular cues that provide an accommodation-vergence mismatch of 0.5 diopter or less. In some other embodiments, the display systems are configured to present images to the viewer using light with wavefront divergence and images with binocular cues that provide an accommodation-vergence mismatch of 0.33 diopter or less. In yet other embodiments, the display systems are configured to present images to the viewer using light with wavefront divergence and images with binocular cues that provide an accommodation-vergence mismatch of 0.25 diopter or less, including about 0.1 diopter or less.

In some embodiments, it will be appreciated that a reference point other than exit pupils of the eyes **210, 220** may be utilized for determining distance, so long as the same

reference point is utilized for the accommodation distance and the vergence distance. For example, the distances could be measured from the cornea to the depth plane, from the retina to the depth plane, from the eyepiece (e.g., a waveguide of the display device) to the depth plane, and so on.

FIG. 5 illustrates aspects of an approach for simulating three-dimensional imagery by modifying wavefront divergence. The display system includes a waveguide **270** that is configured to receive light **770** that is encoded with image information, and to output that light to the user's eye **210**. The waveguide **270** may output the light **650** with a defined amount of wavefront divergence corresponding to the wavefront divergence of a light field produced by a point on a desired depth plane **240**. In some embodiments, the same amount of wavefront divergence is provided for all objects presented on that depth plane. In addition, it will be illustrated that the other eye of the user may be provided with image information from a similar waveguide.

In some embodiments, a single waveguide may be configured to output light with a set amount of wavefront divergence corresponding to a single or limited number of depth planes and/or the waveguide may be configured to output light of a limited range of wavelengths. Consequently, in some embodiments, a plurality or stack of waveguides may be utilized to provide different amounts of wavefront divergence for different depth planes and/or to output light of different ranges of wavelengths.

FIG. 6 illustrates an example of a waveguide stack for outputting image information to a user. A display system **250** includes a stack of waveguides, or stacked waveguide assembly, **260** that may be utilized to provide three-dimensional perception to the eye/brain using a plurality of waveguides **270, 280, 290, 300, 310**. It will be appreciated that the display system **250** may be considered a light field display in some embodiments. In addition, the waveguide assembly **260** may also be referred to as an eyepiece.

In some embodiments, the display system **250** may be configured to provide substantially continuous cues to vergence and multiple discrete cues to accommodation. The cues to vergence may be provided by displaying different images to each of the eyes of the user, and the cues to accommodation may be provided by outputting the light that forms the images with discrete amounts of wavefront divergence. In some embodiments, each discrete level of wavefront divergence corresponds to a particular depth plane and may be provided by a particular one of the waveguides **270, 280, 290, 300, 310**.

With continued reference to FIG. 6, the waveguide assembly **260** may also include a plurality of features **320, 330, 340, 350** between the waveguides. In some embodiments, the features **320, 330, 340, 350** may be one or more lenses. The waveguides **270, 280, 290, 300, 310** and/or the plurality of lenses **320, 330, 340, 350** may be configured to send image information to the eye with various levels of wavefront curvature or light ray divergence. Each waveguide level may be associated with a particular depth plane and may be configured to output image information corresponding to that depth plane. Image injection devices **360, 370, 380, 390, 400** may function as a source of light for the waveguides and may be utilized to inject image information into the waveguides **270, 280, 290, 300, 310**, each of which may be configured, as described herein, to distribute incoming light across each respective waveguide, for output toward the eye **210**. Light exits an output surface **410, 420, 430, 440, 450** of the image injection devices **360, 370, 380, 390, 400** and is injected into a corresponding input surface **460, 470, 480, 490, 500** of the waveguides **270, 280, 290,**

300, 310. In some embodiments, each of the input surfaces 460, 470, 480, 490, 500 may be an edge of a corresponding waveguide, or may be part of a major surface of the corresponding waveguide (that is, one of the waveguide surfaces directly facing the world 510 or the viewer's eye 210). In some embodiments, a single beam of light (e.g. a collimated beam) may be injected into each waveguide to output an entire field of cloned collimated beams that are directed toward the eye 210 at particular angles (and amounts of divergence) corresponding to the depth plane associated with a particular waveguide. In some embodiments, a single one of the image injection devices 360, 370, 380, 390, 400 may be associated with and inject light into a plurality (e.g., three) of the waveguides 270, 280, 290, 300, 310.

In some embodiments, the image injection devices 360, 370, 380, 390, 400 are discrete displays that each produce image information for injection into a corresponding waveguide 270, 280, 290, 300, 310, respectively. In some other embodiments, the image injection devices 360, 370, 380, 390, 400 are the output ends of a single multiplexed display which may, e.g., pipe image information via one or more optical conduits (such as fiber optic cables) to each of the image injection devices 360, 370, 380, 390, 400. It will be appreciated that the image information provided by the image injection devices 360, 370, 380, 390, 400 may include light of different wavelengths, or colors (e.g., different component colors, as discussed herein).

In some embodiments, the light injected into the waveguides 270, 280, 290, 300, 310 is provided by a light projector system 520, which comprises a light module 530, which may include a light emitter, such as a light emitting diode (LED). The light from the light module 530 may be directed to and modified by a light modulator 540, e.g., a spatial light modulator, via a beam splitter 550. The light modulator 540 may be configured to change the perceived intensity of the light injected into the waveguides 270, 280, 290, 300, 310 to encode the light with image information. Examples of spatial light modulators include liquid crystal displays (LCD) including a liquid crystal on silicon (LCOS) displays. It will be appreciated that the image injection devices 360, 370, 380, 390, 400 are illustrated schematically and, in some embodiments, these image injection devices may represent different light paths and locations in a common projection system configured to output light into associated ones of the waveguides 270, 280, 290, 300, 310. In some embodiments, the waveguides of the waveguide assembly 260 may function as ideal lens while relaying light injected into the waveguides out to the user's eyes. In this conception, the object may be the spatial light modulator 540 and the image may be the image on the depth plane.

In some embodiments, the display system 250 may be a scanning fiber display comprising one or more scanning fibers configured to project light in various patterns (e.g., raster scan, spiral scan, Lissajous patterns, etc.) into one or more waveguides 270, 280, 290, 300, 310 and ultimately to the eye 210 of the viewer. In some embodiments, the illustrated image injection devices 360, 370, 380, 390, 400 may schematically represent a single scanning fiber or a bundle of scanning fibers configured to inject light into one or a plurality of the waveguides 270, 280, 290, 300, 310. In some other embodiments, the illustrated image injection devices 360, 370, 380, 390, 400 may schematically represent a plurality of scanning fibers or a plurality of bundles of scanning fibers, each of which are configured to inject light into an associated one of the waveguides 270, 280, 290, 300, 310. It will be appreciated that one or more optical fibers

may be configured to transmit light from the light module 530 to the one or more waveguides 270, 280, 290, 300, 310. It will be appreciated that one or more intervening optical structures may be provided between the scanning fiber, or fibers, and the one or more waveguides 270, 280, 290, 300, 310 to, e.g., redirect light exiting the scanning fiber into the one or more waveguides 270, 280, 290, 300, 310.

A controller 560 controls the operation of one or more of the stacked waveguide assembly 260, including operation of the image injection devices 360, 370, 380, 390, 400, the light source 530, and the light modulator 540. In some embodiments, the controller 560 is part of the local data processing module 140. The controller 560 includes programming (e.g., instructions in a non-transitory medium) that regulates the timing and provision of image information to the waveguides 270, 280, 290, 300, 310 according to, e.g., any of the various schemes disclosed herein. In some embodiments, the controller may be a single integral device, or a distributed system connected by wired or wireless communication channels. The controller 560 may be part of the processing modules 140 or 150 (FIG. 9D) in some embodiments.

With continued reference to FIG. 6, the waveguides 270, 280, 290, 300, 310 may be configured to propagate light within each respective waveguide by total internal reflection (TIR). The waveguides 270, 280, 290, 300, 310 may each be planar or have another shape (e.g., curved), with major top and bottom surfaces and edges extending between those major top and bottom surfaces. In the illustrated configuration, the waveguides 270, 280, 290, 300, 310 may each include out-coupling optical elements 570, 580, 590, 600, 610 that are configured to extract light out of a waveguide by redirecting the light, propagating within each respective waveguide, out of the waveguide to output image information to the eye 210. Extracted light may also be referred to as out-coupled light and the out-coupling optical elements light may also be referred to light extracting optical elements. An extracted beam of light may be outputted by the waveguide at locations at which the light propagating in the waveguide strikes a light extracting optical element. The out-coupling optical elements 570, 580, 590, 600, 610 may, for example, be gratings, including diffractive optical features, as discussed further herein. While illustrated disposed at the bottom major surfaces of the waveguides 270, 280, 290, 300, 310, for ease of description and drawing clarity, in some embodiments, the out-coupling optical elements 570, 580, 590, 600, 610 may be disposed at the top and/or bottom major surfaces, and/or may be disposed directly in the volume of the waveguides 270, 280, 290, 300, 310, as discussed further herein. In some embodiments, the out-coupling optical elements 570, 580, 590, 600, 610 may be formed in a layer of material that is attached to a transparent substrate to form the waveguides 270, 280, 290, 300, 310. In some other embodiments, the waveguides 270, 280, 290, 300, 310 may be a monolithic piece of material and the out-coupling optical elements 570, 580, 590, 600, 610 may be formed on a surface and/or in the interior of that piece of material.

With continued reference to FIG. 6, as discussed herein, each waveguide 270, 280, 290, 300, 310 is configured to output light to form an image corresponding to a particular depth plane. For example, the waveguide 270 nearest the eye may be configured to deliver collimated light (which was injected into such waveguide 270), to the eye 210. The collimated light may be representative of the optical infinity focal plane. The next waveguide up 280 may be configured to send out collimated light which passes through the first lens 350 (e.g., a negative lens) before it may reach the eye

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210; such first lens 350 may be configured to create a slight convex wavefront curvature so that the eye/brain interprets light coming from that next waveguide up 280 as coming from a first focal plane closer inward toward the eye 210 from optical infinity. Similarly, the third up waveguide 290 passes its output light through both the first 350 and second 340 lenses before reaching the eye 210; the combined optical power of the first 350 and second 340 lenses may be configured to create another incremental amount of wavefront curvature so that the eye/brain interprets light coming from the third waveguide 290 as coming from a second focal plane that is even closer inward toward the person from optical infinity than was light from the next waveguide up 280.

The other waveguide layers 300, 310 and lenses 330, 320 are similarly configured, with the highest waveguide 310 in the stack sending its output through all of the lenses between it and the eye for an aggregate focal power representative of the closest focal plane to the person. To compensate for the stack of lenses 320, 330, 340, 350 when viewing/interpreting light coming from the world 510 on the other side of the stacked waveguide assembly 260, a compensating lens layer 620 may be disposed at the top of the stack to compensate for the aggregate power of the lens stack 320, 330, 340, 350 below. Such a configuration provides as many perceived focal planes as there are available waveguide/lens pairings. Both the out-coupling optical elements of the waveguides and the focusing aspects of the lenses may be static (i.e., not dynamic or electro-active). In some alternative embodiments, either or both may be dynamic using electro-active features.

In some embodiments, two or more of the waveguides 270, 280, 290, 300, 310 may have the same associated depth plane. For example, multiple waveguides 270, 280, 290, 300, 310 may be configured to output images set to the same depth plane, or multiple subsets of the waveguides 270, 280, 290, 300, 310 may be configured to output images set to the same plurality of depth planes, with one set for each depth plane. This may provide advantages for forming a tiled image to provide an expanded field of view at those depth planes.

With continued reference to FIG. 6, the out-coupling optical elements 570, 580, 590, 600, 610 may be configured to both redirect light out of their respective waveguides and to output this light with the appropriate amount of divergence or collimation for a particular depth plane associated with the waveguide. As a result, waveguides having different associated depth planes may have different configurations of out-coupling optical elements 570, 580, 590, 600, 610, which output light with a different amount of divergence depending on the associated depth plane. In some embodiments, the light extracting optical elements 570, 580, 590, 600, 610 may be volumetric or surface features, which may be configured to output light at specific angles. For example, the light extracting optical elements 570, 580, 590, 600, 610 may be volume holograms, surface holograms, and/or diffraction gratings. In some embodiments, the features 320, 330, 340, 350 may not be lenses; rather, they may simply be spacers (e.g., cladding layers and/or structures for forming air gaps).

In some embodiments, the out-coupling optical elements 570, 580, 590, 600, 610 are diffractive features that form a diffraction pattern, or “diffractive optical element” (also referred to herein as a “DOE”). Preferably, the DOE’s have a sufficiently low diffraction efficiency so that only a portion of the light of the beam is deflected away toward the eye 210 with each intersection of the DOE, while the rest continues

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to move through a waveguide via TIR. The light carrying the image information is thus divided into a number of related exit beams that exit the waveguide at a multiplicity of locations and the result is a fairly uniform pattern of exit emission toward the eye 210 for this particular collimated beam bouncing around within a waveguide.

In some embodiments, one or more DOEs may be switchable between “on” states in which they actively diffract, and “off” states in which they do not significantly diffract. For instance, a switchable DOE may comprise a layer of polymer dispersed liquid crystal, in which microdroplets comprise a diffraction pattern in a host medium, and the refractive index of the microdroplets may be switched to substantially match the refractive index of the host material (in which case the pattern does not appreciably diffract incident light) or the microdroplet may be switched to an index that does not match that of the host medium (in which case the pattern actively diffracts incident light).

In some embodiments, a camera assembly 630 (e.g., a digital camera, including visible light and infrared light cameras) may be provided to capture images of the eye 210 and/or tissue around the eye 210 to, e.g., detect user inputs and/or to monitor the physiological state of the user. As used herein, a camera may be any image capture device. In some embodiments, the camera assembly 630 may include an image capture device and a light source to project light (e.g., infrared light) to the eye, which may then be reflected by the eye and detected by the image capture device. In some embodiments, the camera assembly 630 may be attached to the frame 80 (FIG. 9D) and may be in electrical communication with the processing modules 140 and/or 150, which may process image information from the camera assembly 630. In some embodiments, one camera assembly 630 may be utilized for each eye, to separately monitor each eye.

With reference now to FIG. 7, an example of exit beams outputted by a waveguide is shown. One waveguide is illustrated, but it will be appreciated that other waveguides in the waveguide assembly 260 (FIG. 6) may function similarly, where the waveguide assembly 260 includes multiple waveguides. Light 640 is injected into the waveguide 270 at the input surface 460 of the waveguide 270 and propagates within the waveguide 270 by TIR. At points where the light 640 impinges on the DOE 570, a portion of the light exits the waveguide as exit beams 650. The exit beams 650 are illustrated as substantially parallel but, as discussed herein, they may also be redirected to propagate to the eye 210 at an angle (e.g., forming divergent exit beams), depending on the depth plane associated with the waveguide 270. It will be appreciated that substantially parallel exit beams may be indicative of a waveguide with out-coupling optical elements that out-couple light to form images that appear to be set on a depth plane at a large distance (e.g., optical infinity) from the eye 210. Other waveguides or other sets of out-coupling optical elements may output an exit beam pattern that is more divergent, which would require the eye 210 to accommodate to a closer distance to bring it into focus on the retina and would be interpreted by the brain as light from a distance closer to the eye 210 than optical infinity.

In some embodiments, a full color image may be formed at each depth plane by overlaying images in each of the component colors, e.g., three or more component colors. FIG. 8 illustrates an example of a stacked waveguide assembly in which each depth plane includes images formed using multiple different component colors. The illustrated embodiment shows depth planes 240a-240f, although more or fewer depths are also contemplated. Each depth plane may have

three or more component color images associated with it, including: a first image of a first color, G; a second image of a second color, R; and a third image of a third color, B. Different depth planes are indicated in the figure by different numbers for diopters (dpt) following the letters G, R, and B. Just as examples, the numbers following each of these letters indicate diopters (1/m), or inverse distance of the depth plane from a viewer, and each box in the figures represents an individual component color image. In some embodiments, to account for differences in the eye's focusing of light of different wavelengths, the exact placement of the depth planes for different component colors may vary. For example, different component color images for a given depth plane may be placed on depth planes corresponding to different distances from the user. Such an arrangement may increase visual acuity and user comfort and/or may decrease chromatic aberrations.

In some embodiments, light of each component color may be outputted by a single dedicated waveguide and, consequently, each depth plane may have multiple waveguides associated with it. In such embodiments, each box in the figures including the letters G, R, or B may be understood to represent an individual waveguide, and three waveguides may be provided per depth plane where three component color images are provided per depth plane. While the waveguides associated with each depth plane are shown adjacent to one another in this drawing for ease of description, it will be appreciated that, in a physical device, the waveguides may all be arranged in a stack with one waveguide per level. In some other embodiments, multiple component colors may be outputted by the same waveguide, such that, e.g., only a single waveguide may be provided per depth plane.

With continued reference to FIG. 8, in some embodiments, G is the color green, R is the color red, and B is the color blue. In some other embodiments, other colors associated with other wavelengths of light, including magenta and cyan, may be used in addition to or may replace one or more of red, green, or blue.

It will be appreciated that references to a given color of light throughout this disclosure will be understood to encompass light of one or more wavelengths within a range of wavelengths of light that are perceived by a viewer as being of that given color. For example, red light may include light of one or more wavelengths in the range of about 620-780 nm, green light may include light of one or more wavelengths in the range of about 492-577 nm, and blue light may include light of one or more wavelengths in the range of about 435-493 nm.

In some embodiments, the light source 530 (FIG. 6) may be configured to emit light of one or more wavelengths outside the visual perception range of the viewer, for example, infrared and/or ultraviolet wavelengths. In addition, the in-coupling, out-coupling, and other light redirecting structures of the waveguides of the display 250 may be configured to direct and emit this light out of the display towards the user's eye 210, e.g., for imaging and/or user stimulation applications.

With reference now to FIG. 9A, in some embodiments, light impinging on a waveguide may need to be redirected to in-couple that light into the waveguide. An in-coupling optical element may be used to redirect and in-couple the light into its corresponding waveguide. FIG. 9A illustrates a cross-sectional side view of an example of a plurality or set 660 of stacked waveguides that each includes an in-coupling optical element. The waveguides may each be configured to output light of one or more different wavelengths, or one or

more different ranges of wavelengths. It will be appreciated that the stack 660 may correspond to the stack 260 (FIG. 6) and the illustrated waveguides of the stack 660 may correspond to part of the plurality of waveguides 270, 280, 290, 300, 310, except that light from one or more of the image injection devices 360, 370, 380, 390, 400 is injected into the waveguides from a position that requires light to be redirected for in-coupling.

The illustrated set 660 of stacked waveguides includes waveguides 670, 680, and 690. Each waveguide includes an associated in-coupling optical element (which may also be referred to as a light input area on the waveguide), with, e.g., in-coupling optical element 700 disposed on a major surface (e.g., an upper major surface) of waveguide 670, in-coupling optical element 710 disposed on a major surface (e.g., an upper major surface) of waveguide 680, and in-coupling optical element 720 disposed on a major surface (e.g., an upper major surface) of waveguide 690. In some embodiments, one or more of the in-coupling optical elements 700, 710, 720 may be disposed on the bottom major surface of the respective waveguide 670, 680, 690 (particularly where the one or more in-coupling optical elements are reflective, deflecting optical elements). As illustrated, the in-coupling optical elements 700, 710, 720 may be disposed on the upper major surface of their respective waveguide 670, 680, 690 (or the top of the next lower waveguide), particularly where those in-coupling optical elements are transmissive, deflecting optical elements. In some embodiments, the in-coupling optical elements 700, 710, 720 may be disposed in the body of the respective waveguide 670, 680, 690. In some embodiments, as discussed herein, the in-coupling optical elements 700, 710, 720 are wavelength selective, such that they selectively redirect one or more wavelengths of light, while transmitting other wavelengths of light. While illustrated on one side or corner of their respective waveguide 670, 680, 690, it will be appreciated that the in-coupling optical elements 700, 710, 720 may be disposed in other areas of their respective waveguide 670, 680, 690 in some embodiments.

As illustrated, the in-coupling optical elements 700, 710, 720 may be laterally offset from one another. In some embodiments, each in-coupling optical element may be offset such that it receives light without that light passing through another in-coupling optical element. For example, each in-coupling optical element 700, 710, 720 may be configured to receive light from a different image injection device 360, 370, 380, 390, and 400 as shown in FIG. 6, and may be separated (e.g., laterally spaced apart) from other in-coupling optical elements 700, 710, 720 such that it substantially does not receive light from the other ones of the in-coupling optical elements 700, 710, 720.

Each waveguide also includes associated light distributing elements, with, e.g., light distributing elements 730 disposed on a major surface (e.g., a top major surface) of waveguide 670, light distributing elements 740 disposed on a major surface (e.g., a top major surface) of waveguide 680, and light distributing elements 750 disposed on a major surface (e.g., a top major surface) of waveguide 690. In some other embodiments, the light distributing elements 730, 740, 750, may be disposed on a bottom major surface of associated waveguides 670, 680, 690, respectively. In some other embodiments, the light distributing elements 730, 740, 750, may be disposed on both top and bottom major surface of associated waveguides 670, 680, 690, respectively; or the light distributing elements 730, 740,

750, may be disposed on different ones of the top and bottom major surfaces in different associated waveguides 670, 680, 690, respectively.

The waveguides 670, 680, 690 may be spaced apart and separated by, e.g., gas, liquid, and/or solid layers of material. For example, as illustrated, layer 760a may separate waveguides 670 and 680; and layer 760b may separate waveguides 680 and 690. In some embodiments, the layers 760a and 760b are formed of low refractive index materials (that is, materials having a lower refractive index than the material forming the immediately adjacent one of waveguides 670, 680, 690). Preferably, the refractive index of the material forming the layers 760a, 760b is 0.05 or more, or 0.10 or less than the refractive index of the material forming the waveguides 670, 680, 690. Advantageously, the lower refractive index layers 760a, 760b may function as cladding layers that facilitate total internal reflection (TIR) of light through the waveguides 670, 680, 690 (e.g., TIR between the top and bottom major surfaces of each waveguide). In some embodiments, the layers 760a, 760b are formed of air. While not illustrated, it will be appreciated that the top and bottom of the illustrated set 660 of waveguides may include immediately neighboring cladding layers.

Preferably, for ease of manufacturing and other considerations, the material forming the waveguides 670, 680, 690 are similar or the same, and the material forming the layers 760a, 760b are similar or the same. In some embodiments, the material forming the waveguides 670, 680, 690 may be different between one or more waveguides, and/or the material forming the layers 760a, 760b may be different, while still holding to the various refractive index relationships noted above.

With continued reference to FIG. 9A, light rays 770, 780, 790 are incident on the set 660 of waveguides. It will be appreciated that the light rays 770, 780, 790 may be injected into the waveguides 670, 680, 690 by one or more image injection devices 360, 370, 380, 390, 400 (FIG. 6).

In some embodiments, the light rays 770, 780, 790 have different properties, e.g., different wavelengths or different ranges of wavelengths, which may correspond to different colors. The in-coupling optical elements 700, 710, 720 each deflect the incident light such that the light propagates through a respective one of the waveguides 670, 680, 690 by TIR. In some embodiments, the in-coupling optical elements 700, 710, 720 each selectively deflect one or more particular wavelengths of light, while transmitting other wavelengths to an underlying waveguide and associated in-coupling optical element.

For example, in-coupling optical element 700 may be configured to deflect ray 770, which has a first wavelength or range of wavelengths, while transmitting rays 780 and 790, which have different second and third wavelengths or ranges of wavelengths, respectively. The transmitted ray 780 impinges on and is deflected by the in-coupling optical element 710, which is configured to deflect light of a second wavelength or range of wavelengths. The ray 790 is deflected by the in-coupling optical element 720, which is configured to selectively deflect light of third wavelength or range of wavelengths.

With continued reference to FIG. 9A, the deflected light rays 770, 780, 790 are deflected so that they propagate through a corresponding waveguide 670, 680, 690; that is, the in-coupling optical elements 700, 710, 720 of each waveguide deflects light into that corresponding waveguide 670, 680, 690 to in-couple light into that corresponding waveguide. The light rays 770, 780, 790 are deflected at angles that cause the light to propagate through the respec-

tive waveguide 670, 680, 690 by TIR. The light rays 770, 780, 790 propagate through the respective waveguide 670, 680, 690 by TIR until impinging on the waveguide's corresponding light distributing elements 730, 740, 750.

With reference now to FIG. 9B, a perspective view of an example of the plurality of stacked waveguides of FIG. 9A is illustrated. As noted above, the in-coupled light rays 770, 780, 790, are deflected by the in-coupling optical elements 700, 710, 720, respectively, and then propagate by TIR within the waveguides 670, 680, 690, respectively. The light rays 770, 780, 790 then impinge on the light distributing elements 730, 740, 750, respectively. The light distributing elements 730, 740, 750 deflect the light rays 770, 780, 790 so that they propagate towards the out-coupling optical elements 800, 810, 820, respectively.

In some embodiments, the light distributing elements 730, 740, 750 are orthogonal pupil expanders (OPE's). In some embodiments, the OPE's deflect or distribute light to the out-coupling optical elements 800, 810, 820 and, in some embodiments, may also increase the beam or spot size of this light as it propagates to the out-coupling optical elements. In some embodiments, the light distributing elements 730, 740, 750 may be omitted and the in-coupling optical elements 700, 710, 720 may be configured to deflect light directly to the out-coupling optical elements 800, 810, 820. For example, with reference to FIG. 9A, the light distributing elements 730, 740, 750 may be replaced with out-coupling optical elements 800, 810, 820, respectively. In some embodiments, the out-coupling optical elements 800, 810, 820 are exit pupils (EP's) or exit pupil expanders (EPE's) that direct light in a viewer's eye 210 (FIG. 7). It will be appreciated that the OPE's may be configured to increase the dimensions of the eye box in at least one axis and the EPE's may be to increase the eye box in an axis crossing, e.g., orthogonal to, the axis of the OPEs. For example, each OPE may be configured to redirect a portion of the light striking the OPE to an EPE of the same waveguide, while allowing the remaining portion of the light to continue to propagate down the waveguide. Upon impinging on the OPE again, another portion of the remaining light is redirected to the EPE, and the remaining portion of that portion continues to propagate further down the waveguide, and so on. Similarly, upon striking the EPE, a portion of the impinging light is directed out of the waveguide towards the user, and a remaining portion of that light continues to propagate through the waveguide until it strikes the EP again, at which time another portion of the impinging light is directed out of the waveguide, and so on. Consequently, a single beam of in-coupled light may be "replicated" each time a portion of that light is redirected by an OPE or EPE, thereby forming a field of cloned beams of light, as shown in FIG. 6. In some embodiments, the OPE and/or EPE may be configured to modify a size of the beams of light.

Accordingly, with reference to FIGS. 9A and 9B, in some embodiments, the set 660 of waveguides includes waveguides 670, 680, 690; in-coupling optical elements 700, 710, 720; light distributing elements (e.g., OPE's) 730, 740, 750; and out-coupling optical elements (e.g., EP's) 800, 810, 820 for each component color. The waveguides 670, 680, 690 may be stacked with an air gap/cladding layer between each one. The in-coupling optical elements 700, 710, 720 redirect or deflect incident light (with different in-coupling optical elements receiving light of different wavelengths) into its waveguide. The light then propagates at an angle which will result in TIR within the respective waveguide 670, 680, 690. In the example shown, light ray 770 (e.g., blue light) is deflected by the first in-coupling optical element 700, and

then continues to bounce down the waveguide, interacting with the light distributing element (e.g., OPE's) 730 and then the out-coupling optical element (e.g., EPs) 800, in a manner described earlier. The light rays 780 and 790 (e.g., green and red light, respectively) will pass through the waveguide 670, with light ray 780 impinging on and being deflected by in-coupling optical element 710. The light ray 780 then bounces down the waveguide 680 via TIR, proceeding on to its light distributing element (e.g., OPEs) 740 and then the out-coupling optical element (e.g., EP's) 810. Finally, light ray 790 (e.g., red light) passes through the waveguide 690 to impinge on the light in-coupling optical elements 720 of the waveguide 690. The light in-coupling optical elements 720 deflect the light ray 790 such that the light ray propagates to light distributing element (e.g., OPEs) 750 by TIR, and then to the out-coupling optical element (e.g., EPs) 820 by TIR. The out-coupling optical element 820 then finally out-couples the light ray 790 to the viewer, who also receives the out-coupled light from the other waveguides 670, 680.

FIG. 9C illustrates a top-down plan view of an example of the plurality of stacked waveguides of FIGS. 9A and 9B. As illustrated, the waveguides 670, 680, 690, along with each waveguide's associated light distributing element 730, 740, 750 and associated out-coupling optical element 800, 810, 820, may be vertically aligned. However, as discussed herein, the in-coupling optical elements 700, 710, 720 are not vertically aligned; rather, the in-coupling optical elements are preferably non-overlapping (e.g., laterally spaced apart as seen in the top-down view). As discussed further herein, this nonoverlapping spatial arrangement facilitates the injection of light from different resources into different waveguides on a one-to-one basis, thereby allowing a specific light source to be uniquely coupled to a specific waveguide. In some embodiments, arrangements including nonoverlapping spatially-separated in-coupling optical elements may be referred to as a shifted pupil system, and the in-coupling optical elements within these arrangements may correspond to sub pupils.

FIG. 9D illustrates an example of wearable display system 60 into which the various waveguides and related systems disclosed herein may be integrated. In some embodiments, the display system 60 is the system 250 of FIG. 6, with FIG. 6 schematically showing some parts of that system 60 in greater detail. For example, the waveguide assembly 260 of FIG. 6 may be part of the display 70.

With continued reference to FIG. 9D, the display system 60 includes a display 70, and various mechanical and electronic modules and systems to support the functioning of that display 70. The display 70 may be coupled to a frame 80, which is wearable by a display system user or viewer 90 and which is configured to position the display 70 in front of the eyes of the user 90. The display 70 may be considered eyewear in some embodiments. In some embodiments, a speaker 100 is coupled to the frame 80 and configured to be positioned adjacent the ear canal of the user 90 (in some embodiments, another speaker, not shown, may optionally be positioned adjacent the other ear canal of the user to provide stereo/shapeable sound control). The display system 60 may also include one or more microphones 110 or other devices to detect sound. In some embodiments, the microphone is configured to allow the user to provide inputs or commands to the system 60 (e.g., the selection of voice menu commands, natural language questions, etc.), and/or may allow audio communication with other persons (e.g., with other users of similar display systems. The microphone may further be configured as a peripheral sensor to collect

audio data (e.g., sounds from the user and/or environment). In some embodiments, the display system may also include a peripheral sensor 120a, which may be separate from the frame 80 and attached to the body of the user 90 (e.g., on the head, torso, an extremity, etc. of the user 90). The peripheral sensor 120a may be configured to acquire data characterizing a physiological state of the user 90 in some embodiments. For example, the sensor 120a may be an electrode.

With continued reference to FIG. 9D, the display 70 is operatively coupled by communications link 130, such as by a wired lead or wireless connectivity, to a local data processing module 140 which may be mounted in a variety of configurations, such as fixedly attached to the frame 80, fixedly attached to a helmet or hat worn by the user, embedded in headphones, or otherwise removably attached to the user 90 (e.g., in a backpack-style configuration, in a belt-coupling style configuration). Similarly, the sensor 120a may be operatively coupled by communications link 120b, e.g., a wired lead or wireless connectivity, to the local processor and data module 140. The local processing and data module 140 may comprise a hardware processor, as well as digital memory, such as non-volatile memory (e.g., flash memory or hard disk drives), both of which may be utilized to assist in the processing, caching, and storage of data. Optionally, the local processor and data module 140 may include one or more central processing units (CPUs), graphics processing units (GPUs), dedicated processing hardware, and so on. The data may include data a) captured from sensors (which may be, e.g., operatively coupled to the frame 80 or otherwise attached to the user 90), such as image capture devices (such as cameras), microphones, inertial measurement units, accelerometers, compasses, GPS units, radio devices, gyros, and/or other sensors disclosed herein; and/or b) acquired and/or processed using remote processing module 150 and/or remote data repository 160 (including data relating to virtual content), possibly for passage to the display 70 after such processing or retrieval. The local processing and data module 140 may be operatively coupled by communication links 170, 180, such as via a wired or wireless communication links, to the remote processing module 150 and remote data repository 160 such that these remote modules 150, 160 are operatively coupled to each other and available as resources to the local processing and data module 140. In some embodiments, the local processing and data module 140 may include one or more of the image capture devices, microphones, inertial measurement units, accelerometers, compasses, GPS units, radio devices, and/or gyros. In some other embodiments, one or more of these sensors may be attached to the frame 80, or may be standalone structures that communicate with the local processing and data module 140 by wired or wireless communication pathways.

With continued reference to FIG. 9D, in some embodiments, the remote processing module 150 may comprise one or more processors configured to analyze and process data and/or image information, for instance including one or more central processing units (CPUs), graphics processing units (GPUs), dedicated processing hardware, and so on. In some embodiments, the remote data repository 160 may comprise a digital data storage facility, which may be available through the internet or other networking configuration in a "cloud" resource configuration. In some embodiments, the remote data repository 160 may include one or more remote servers, which provide information, e.g., information for generating augmented reality content, to the local processing and data module 140 and/or the remote processing module 150. In some embodiments, all data is stored and

all computations are performed in the local processing and data module, allowing fully autonomous use from a remote module. Optionally, an outside system (e.g., a system of one or more processors, one or more computers) that includes CPUs, GPUs, and so on, may perform at least a portion of processing (e.g., generating image information, processing data) and provide information to, and receive information from, modules **140**, **150**, **160**, for instance via wireless or wired connections.

Metasurfaces

FIGS. **10A** and **10B** illustrate examples of cross-sectional side and top down views, respectively, of a metasurface **2002** according to some embodiments. A substrate **2000** has a surface **2000a** on which a metasurface **2002** comprising a plurality of metasurface unit cells **2010** is disposed. The unit cells each include a plurality of nanobeams **2020a**, **2020b** formed of an optically transmissive material. The nanobeams **2020a**, **2020b** may be ridges (or nanowires), which are laterally elongated into and out of the page and define trenches between neighboring nanobeams. In some embodiments, the nanobeams **2020a**, **2020b** may be linear. Preferably, the nanobeams **2020a**, **2020b** are continuous along their lengths, which can have benefits for providing a high diffraction efficiency. In some other embodiments, the nanobeams **2020a**, **2020b** may be discontinuous along their lengths, e.g., the nanobeams **2020a**, **2020b** may each extend along a line, with gaps in the nanobeams **2020a**, **2020b** along those lines.

The unit cells **2010** may repeat at regular intervals across the surface **2000a**, and may be parallel to one another such that the nanobeams **2020a**, **2020b** are also parallel to one another. The unit cells **2010** may have a width P , which is the distance between identical points of directly neighboring unit cells **2010**. In some embodiments, P may be in the range of 10 nm to 1 μm , including 10 nm to 500 nm or 300 nm to 500 nm. It will be appreciated that P may be considered the pitch of the unit cells **2010** and may be substantially constant across a grating formed by those unit cells. In some other embodiments, P may vary across the surface **2000a**.

Preferably, the refractive index of the material forming the nanobeams **2020a**, **2020b** is higher than the refractive index of the substrate **2000**. In some embodiments, the substrate **2000** may be a waveguide, and may correspond to the waveguides **270**, **280**, **290**, **300**, **310** (FIG. **6**) and/or waveguides **670**, **680**, and **690** (FIG. **9A**). In such applications, the substrate preferably has a relatively high refractive index, e.g., 1.5, 1.6, 1.7, 1.8, 1.9, or higher, which can provide benefits for increasing the field of view of a display that forms an image by outputting light from that substrate **2000**. Examples of materials for forming the substrate **2000** include glass (e.g., doped glass), lithium niobate, plastic, a polymer, sapphire, or other optically transmissive material. In some embodiments, the refractive index of the material forming the nanobeams **2020a**, **2020b** may be 2.0 or higher, 2.5 or higher, 3.0 or higher, 3.3 or higher, or 3.5 or higher. Examples of materials for forming the nanobeams **2020a**, **2020b** include silicon-containing materials (e.g., amorphous or polysilicon, and silicon nitride), oxides, and gallium phosphide. Examples of oxides include titanium oxide, zirconium oxide, and zinc oxide. Preferably, the material forming the nanobeams **2020a**, **2020b** is the same, which has advantages for simplifying fabrication of the metasurface **2002**.

With continued reference to FIGS. **10A** and **10B**, one of the nanobeams **2020b** has a width NW_2 that is larger than the width NW_1 of the other of the illustrated nanobeams **2020a**. In some embodiments, the widths NW_1 and NW_2 are each in

the range of 10 nm to 1 μm , including 10 nm to 300 nm, with NW_1 being greater than NW_2 as noted above. As illustrated, the nanobeams **2020a**, **2020b** may be separated by a gap in the range of 10 nm to 1 μm wide, including 10 nm to 300 nm wide. As also illustrated, the nanobeams **2020a**, **2020b** have a height h_{nw} , which may be in the range of 10 nm to 1 μm , including 10 nm to 450 nm. Preferably, the heights of the nanobeams **2020a**, **2020b** are substantially equal.

As disclosed herein, the various dimensions of features of the unit cells **2010** and nanobeams **2020a**, **2020b** may vary depending upon the properties of the materials used to form the metasurface **2002** and the properties of surrounding structures, such as the substrate **2000**. In some embodiments, the height h_{nw} of the nanobeams **2020a**, **2020b** may vary depending upon the refractive index of the material used for those nanobeams. In some embodiments, the heights of the nanobeams may be 10 nm to 450 nm where a refractive index of the material is more than 3.3; and 10 nm to 1 μm where the refractive index is 3.3 or less. As another example, the height of the nanobeams may be 10 nm to 450 nm where the nanobeams are formed of silicon (e.g., amorphous or polysilicon).

With continued reference to FIGS. **10A** and **10B**, the metasurface **2002** illustrated in these figures works in the transmissive mode. Light rays **2021a**, **2021b** are redirected upon propagating through the metasurface **2002** formed by the nanobeams **2020a**, **2020b**. As illustrated, the light ray **2021a** is incident on the metasurface **2002** at an angle α relative to the normal to the surface **2000a**. Preferably, the angle α is within the angular bandwidth for the metasurface **2002** such that the light ray **2021a** is redirected by the metasurface **2002** to propagate within the substrate **2000** at angles that facilitate total internal reflection within that substrate **2000**. As illustrated, the light ray **2021b** is redirected such that it makes out an angle θ_{TIR} with the normal to the surface **2000a**. Preferably, the angle θ_{TIR} is within a range of angles that facilitate total internal reflection within the substrate **2000**. As disclosed herein, in some embodiments, the metasurface **2002** may be utilized as an incoupling optical element (e.g., as one or more of the incoupling optical elements **700**, **710**, **720** (FIG. **9A**)) to incouple incident light such that the light propagates through the substrate **2000** via total internal reflection.

The metasurface **2002** will also deflect light impinging on it from within the substrate **2000**. Taking advantage of this functionality, in some embodiments, the metasurfaces disclosed herein may be applied to form outcoupling optical elements, such as one or more of the outcoupling optical elements **570**, **580**, **590**, **600**, **610** (FIG. **6**) or **800**, **810**, **820** (FIG. **9B**) instead of, or in addition to, forming an incoupling optical element at different locations on the surface **2000a**. Where different waveguides have different associated component colors, it will be appreciated that the outcoupling optical elements and/or the incoupling optical elements associated with each waveguide made have a geometric size and/or periodicity specific for the wavelengths or colors of light that the waveguide is configured to propagate. Thus, different waveguides may have metasurfaces with different geometric sizes and/or periodicities. As examples, the metasurfaces for incoupling or outcoupling red, green, or blue light may have geometric sizes and/or periodicities (itches) configured to redirect or diffract light at wavelengths of, e.g., 638 nm, 520 nm, and 455 nm, respectively. In some embodiments, the geometric size and periodicity of the nanobeams **2020a**, **2020b** and unit cells **2010** increases as wavelengths become longer, and the height or thickness

of one or both of the nanobeams **2020a**, **2020b** also increase as wavelengths become longer.

In some embodiments, where the metasurface is **2002** are utilized as outcoupling optical elements, the metasurfaces **2002** may have geometric sizes and/or pitches that cause the metasurfaces to impart optical power onto the diffracted light. For example, the metasurfaces may be configured to cause light to exit the metasurface in diverging or converging directions. Different portions of the metasurface may have different pitches, which cause different light rays to deflect in different directions, e.g., so that the light rays diverge or converge.

In some other embodiments, the metasurface **2002** may redirect light such that the light propagates away from the metasurface **2002** as collimated rays of light. For example, where collimated light impinges on the metasurface **2002** at similar angles, the metasurface **2002** may have consistent geometric sizes and a consistent pitch across the entirety of the metasurface **2002** to redirect the light at similar angles.

With reference now to FIGS. **11A-11B**, the metasurface **2002** may deflect light in a “reflective mode” where the redirected light remains on the same side of the metasurface **2002** before and after impinging on the metasurface. FIG. **11A** illustrates an example of a cross-sectional side view of a metasurface configured to function in a reflective mode, and FIG. **11B** illustrates an example of a cross-sectional, top-down view of the metasurfaces of FIG. **11A** as viewed on the plane **11B**. As shown, the nanobeams **2020a**, **2020b** of the metasurface **2002** may be embedded in a reflective layer **2100**. The reflective layer **2100** may be formed of a reflective material, e.g., a metal, such as aluminum, silver, gold, and copper. Preferably, the material forming the reflective layer **2100** fills the spaces between the nanobeams **2020a**, **2020b** and between the unit cells **2010**. In addition, the height or thickness h_r of the reflective layer **2100** may be greater than the height h_{nw} of the nanobeams **2020a**, **2020b**. In some embodiments, the height h_r may be 150 nm or thicker, or 1 μ m or thicker. Preferably, the reflective layer **2100** is sufficiently thick to block incident light, with h_r being greater than the optical depth of the layer **2100**. It will be appreciated that the ranges of the dimensions of the various features forming a unit cell **2010** are similar to that discussed herein with respect to FIGS. **10A** and **10B**.

With reference now to FIGS. **12-13**, another example of a reflective mode metasurface is illustrated. FIG. **12** illustrates an example of a cross-sectional side view of the metasurface **2002** configured to function in a reflective mode, and FIG. **13** illustrates an example of a cross-sectional, top-down view of the metasurface of FIG. **12** as viewed on the plane **13** of FIG. **13**. As illustrated, the nanobeams **2020a**, **2020b** are embedded in an optically transmissive spacer layer **2110**. In these embodiments, the reflective layer **2100** is disposed directly on the surface of the spacer layer **2110** opposite the substrate **2000**. The spacer layer **2110** has a height or thickness h_{sl} which is greater than the height of the nanobeams **2020a**, **2020b** by a height h_s , thereby spacing the nanobeams **2020a**, **2020b** from reflective layer **2100** by a distance equal to h_s . In some embodiments, the height h_s may be within the range of 5 nm to 1 μ m, including 10 nm to 300 nm. It will be appreciated that examples of suitable materials for the spacer layer **2100** can include material that may be deposited by spin on coat, including poly(methyl methacrylate) (PMMA), spin-on glass, e-beam resist or photo-resist, and polymer. In some embodiments, the spacer layer has a refractive index of 1 to 2.

In some embodiments, the substrate **2000** may be provided with both transmissive metasurfaces and reflective metasurfaces. FIG. **14A** illustrates an example of a cross-sectional side view of the substrate **2000** having transmissive and reflective metasurfaces **2002a**, **2002b**, respectively. In some embodiments, the transmissive and reflective metasurfaces **2002a**, **2002b** may be on opposing sides of the substrate. FIG. **14B** illustrates an example of a top-down view of the metasurface **2002a** of FIG. **14A**. FIG. **14C** illustrates an example of a top-down view of the metasurface **2002b** of FIG. **14A** viewed on the plane **14C** of FIG. **14A**.

With reference to FIG. **14A**, metasurface **2002a** includes a plurality of unit cells **2010a** which include nanobeams **2020a**, **2020b**. Similarly, the metasurface **2002b** includes a plurality of unit cells **2010b** which include nanobeams **2020c**, **2020d**. As with the nanobeams **2020a**, **2020b**, one of the nanobeams **2020c**, **2020d** is wider than the other. As disclosed herein, the dimensions of the features of the unit cells **2010a**, **2010b** may be selected based upon the wavelengths of light that the metasurfaces are configured to redirect, and the desired degree of redirection. Where the metasurface is configured to redirect light of different wavelengths, the widths of the nanobeams **2020a** and **2020c** may be different from one another, and/or the widths of the nanobeams **2020b** and **2020d** may be different from one another. For example, the metasurface **2002a** may be configured to redirect light corresponding to the color green, while the metasurface **2002b** may be configured to redirect light corresponding to the color red. In some embodiments, such an arrangement in which each metasurface is configured to redirect light of a different range of wavelengths may advantageously reduce the size of a waveguide stack in which different waveguides are used to propagate light of different wavelengths. Advantageously, the metasurfaces **2002a**, **2002b** may be used as incoupling optical elements and/or outcoupling optical elements to allow a single waveguide to be used to guide light corresponding to different component colors, thereby avoiding the use of one waveguide.

As illustrated, the metasurface **2002a** functions in the transmissive mode and selectively redirects light ray **2040a**, while allowing light ray **2040b** to propagate through the metasurface without being redirected. The light ray **2040b** then impinges on the reflective-mode metasurface **2002b**, which reflects the light ray **2040b** such that it propagates in a desired direction (which is different from the direction expected for a specular reflector).

With reference now to FIGS. **15A-15E**, an example of a process flow for forming a transmissive metasurface is illustrated. With reference to FIG. **15A**, a layer **2020** of an optically transmissive material for forming the nanobeams **2020a**, **2020b** is deposited on the substrate **2000**. The deposition may be accomplished using, e.g., a vapor deposition process such as chemical vapor deposition (CVD), including plasma-enhanced chemical vapor deposition. Subsequently, with reference to FIG. **15B**, a selectively definable material, e.g., a resist (such as a nanoimprint resist) is deposited on the layer **2022**. The resist **2022** may be deposited by jet coating (e.g., inkjet printing), which may provide advantages for forming exceptionally thin layers, and also layers with varying composition and/or thickness.

With reference to FIG. **15C**, an imprint template or master **2024** is brought into contact with the resist **2022** to pattern that resist. In some other embodiments, the pattern in the imprint template **2024** may be formed by, e.g., lithography, including e-beam lithography or EUV lithography.

With reference to FIG. 15D, the pattern formed in the resist layer **2022** is transferred to the optically transmissive layer **2020**. It will be appreciated that this pattern transfer may be accomplished using an etch selective for the material forming the optically transmissive layer **2020** relative to other exposed materials. In some embodiments, the pattern transfer etch may be an anisotropic etch, such as a reactive ion etch. Subsequently, in some embodiments, the resist layer **2022** may be removed using, e.g., an ashing process.

With reference now to FIG. 15E, a plurality of unit cells **2010** comprising nanobeams **2020a**, **2020b** are formed. It will be appreciated that while shown schematically as having similar widths for ease of illustration, the nanobeams **2020a**, **2020b** have different widths, as disclosed herein.

FIGS. 16A and 16B illustrate scanning electron microscope images of a metasurface. The metasurface was formed generally as described with respect to FIGS. 15A-15E, with the resist being patterned by electron beam lithography. Advantageously, highly uniform rows of material corresponding to the nanobeams **2020a**, **2020b** were formed. As shown in FIG. 16B, each nanobeam has a substantially uniform cross-sectional shape, as seen in the illustrated side view.

While not illustrated, it will be appreciated that reflective-mode metasurfaces may be formed through additional processing of the structure shown in FIG. 15E. For example, a reflective material may be deposited in the open volumes between the nanobeams **2020a**, **2020b**, and over those nanobeams to form the structure illustrated in FIGS. 11A and 11B. In some other embodiments, the nanobeams **2020a**, **2020b** may be formed by etching trenches in the reflective layer and subsequently filling the trenches with the material of the nanobeams **2020a**, **2020b**.

As another example, the structure illustrated in FIG. 12 may be formed by depositing a layer of optically-transmissive spacer material on and between the nanobeams **2020a**, **2020b**. The reflective layer may subsequently be deposited on the spacer layer. In some embodiments, the depositions may be accomplished using vapor deposition processes, e.g., chemical vapor deposition (CVD) processes and/or physical vapor deposition (PVD) processes.

As discussed herein, metasurfaces according to various embodiments provide highly uniform diffraction efficiency over a wide range of incident angles. FIG. 17 illustrates an example of a plot showing the diffraction efficiency versus angle of incidence of light for a transmissive metasurface. Advantageously, the diffraction efficiency over a span of angles ranging about 50° is highly uniform.

High uniformity is also provided by various embodiments of a reflective metasurface. FIGS. 18A-18C illustrate examples of plots showing the diffraction efficiency versus angle of incidence of light for a reflective metasurface. The wavelengths of incident light are different for each of FIGS. 18A-18C. Advantageously, the plots are highly flat over a large range of incident angles. In addition, the plots are advantageously similar for different wavelengths corresponding to the colors red, green, and blue. Such uniformity may be beneficially applied to display systems which utilize different component colors. The uniformity of the diffraction may aid in the formation of high quality images with high color accuracy.

It has also been found that the diffraction efficiency of the metasurfaces is highly dependent upon the polarization of the incident light. FIGS. 19A and 19B illustrate examples of plots showing the polarization sensitivity of the transmissive metasurface of FIGS. 10A and 10B. As shown in FIG. 19A, the diffraction efficiency is high for incident light with a

polarization that is parallel to the nanobeams forming the asymmetric grating. However, light with a polarization that is perpendicular to the nanobeams has low diffraction efficiency. Given this sensitivity to polarization, as noted herein, the metasurface may advantageously be utilized as a polarizing beam splitter. Preferably, the metasurface provides extinction ratios of 5 or more, 7 or more, or 9 or more for light of different polarizations.

As discussed herein, the amplitude and phase of light redirected by the metasurfaces disclosed herein are dependent upon the widths of the nanobeams forming the metal surfaces. FIG. 20 illustrates plots of amplitude and phase shift versus nanobeam width for the metasurface of FIGS. 10A and 10B. As indicated by the plots, the widths of the nanobeams or nanowires may be adjusted to manipulate the amplitude and phase of the redirected light.

With reference now to FIG. 21A, in some embodiments, the metasurface may include a multilevel asymmetric grating. FIG. 21A illustrates an example of a cross-sectional side view of a multilevel metasurface **2008** that includes a plurality of levels of optically transmissive materials. It will be appreciated that the cross-sectional side view is taken on a plane orthogonal to the elongate axis of the illustrated nanobeams **2020a**, **2020b**. Nanobeams **2020a**, **2020b** are formed on the surface **2000a** of the substrate **2000**. As illustrated, in some embodiments, the metasurface **2008** is a bi-level structure having lowermost and uppermost levels **2012**, **2014**, respectively. The lowermost level **2012** includes the nanobeams **2020a**, **2020b** formed of a first optically transmissive material and masses **2030c** of a second optically transmissive material between the nanobeams **2020a**, **2020b**. The uppermost level **2014** may be directly vertically adjacent the nanobeams **2020a**, **2020b** and includes uppermost level nanobeams **2030a** of the second optically transmissive material formed directly on the nanobeams **2020a** and uppermost level nanobeams **2030b** of the second optically transmissive material formed directly on the nanobeams **2020b**. It will be appreciated that the uppermost level nanobeams **2030a**, **2030b** of the second optically transmissive material may contact the nanobeams **2020a**, **2020b**. As illustrated, on the uppermost level **2014**, the nanobeams **2030a**, **2030b** of the second optically transmissive material may be localized on the surface of the nanobeams **2020a**, **2020b**, forming plateaus of material spaced apart from other localized deposits (or plateaus) of the second optically transmissive material.

With continued reference to FIG. 21A, preferably, the refractive index of the second optically transmissive material forming the nanobeams **2030a**, **2030b** and masses **2030c** is higher than the refractive index of both the first optically transmissive material forming the nanobeams **2020a**, **2020b**, and the material forming the substrate **2000**. In some embodiments, the refractive index of the first optically transmissive material forming the nanobeams **2020a**, **2020b** is lower than or similar to the refractive index of the material forming the substrate **2000**.

With continued reference to FIG. 21A, the first optically transmissive material of the nanobeams **2020a**, **2020b** is preferably a material that may be patterned, e.g., by lithography and etch processes. More preferably, the first optically transmissive material is a nanoimprint resist that may be patterned by nanoimprinting. As discussed herein, the second optically transmissive material forming the nanobeams **2030a**, **2030b** and masses **2030c** may have a higher refractive index than both the first optically transmissive material of the nanobeams **2020a**, **2020b** and the material forming the substrate **2000**. In some embodiments, the refractive index

of the second optically transmissive material is higher than 1.6, 1.7, 1.8, or 1.9. Examples of materials for the second optically transmissive material include semiconductor materials, including silicon-containing materials, and oxides. Examples of silicon-containing materials include silicon nitride and silicon carbide. Examples of oxides include titanium oxide, zirconium oxide, and zinc oxide. In some embodiments, the second optically transmissive material may have lower optical transparency than these oxides. For example, the second optically transmissive material may be silicon or its derivatives. In some embodiments, the first and second optically transmissive materials are amorphous solid state materials, or crystalline solid state materials. Without being limited by theory, amorphous materials may be desirable in some applications, since they may be formed at lower temperatures and over a wider range of surfaces than some crystalline materials. In some embodiments, each of the first and second optically transmissive materials forming the features **2020a**, **2020b**, **2030a**, **2030b**, **2030c** may be one of an amorphous or crystalline semiconductor material.

As discussed above, in some embodiments, the widths NW_1 , NW_2 of the nanobeams **2020a**, **2020b**, respectively, forming the unit cells **2010** may be in the range of 10 nm to 1 μ m, including 10 nm to 300 nm or 10 nm to 250 nm. The nanobeams **2020a**, **2020b** of a unit cell **2010** may be separated by a gap in the range of 5 nm to 1 μ m wide, including 10 nm to 1 μ m wide or 10 nm to 300 nm wide. The pitch P of the unit cells **2010** may be in the range of 10 nm to 1 μ m, including 10 nm to 500 nm, or 300 nm to 500 nm. In some embodiments, the heights h_{nw} of the nanobeams **2020a**, **2020b** may be in the range of 10 nm to 1 μ m, including 10 nm to 500 nm or 10 nm to 450 nm. The heights h_m of the masses **2030c** may be in the range of 10 nm to 1 μ m, including 10 nm to 600 nm. Preferably, the heights of the nanobeams **2030a**, **2030b** and masses **2030c** are substantially similar.

It has been found that the dimensions of features of the unit cells may vary depending upon the properties of the materials used to form the metasurface. For example, the height of the nanobeams may vary depending upon the refractive index of the material used for those nanobeams. In some embodiments, the heights of the nanobeams may be 10 nm to 450 nm where a refractive index of the material is more than 3.3; and 10 nm to 1 μ m where the refractive index is 3.3 or less. As another example, the height of the nanobeams may be 10 nm to 450 nm where the nanobeams are formed of silicon (e.g., amorphous or polysilicon). In some embodiments, the heights of the material of the nanobeams **2030a**, **2030b** and masses **2030c** may be in the range of 10 nm to 1 μ m, including 10 nm to 600 nm.

Within the above noted ranges of dimensions, it will be appreciated that, in some embodiments, the metasurface may function in a primarily reflective mode or a primarily transmissive mode, depending upon the appropriate selection of dimensions in conjunction with materials for the features **2030a**, **2030b**, **2030c**. For example, for a given wavelength of light, the thickness of the features **2030a**, **2030b**, **2030c** for a metasurface **2008** working in the reflective mode may be lower than the thickness of the features **2030a**, **2030b**, **2030c** for a metasurface working in the transmissive mode. In addition, in either the transmissive or reflective mode, the use of a higher refractive index material for the features **2030a**, **2030b**, **2030c** may allow a reduction in the thickness of those features while achieving similar light redirecting properties.

With continued reference to FIG. 21A, the metasurface **2008** is working in the reflective mode, with incident light

ray **2200** impinging on the metasurface **2008** and being redirected by diffraction at an angle such that it propagates through the substrate **2000** by total internal reflection. In some embodiments, the heights of the features **2030a**, **2030b**, **2030c** may be lower than the heights of the nanobeams **2020a**, **2020b**, as illustrated. It will be appreciated that light may be understood to pass twice through metasurfaces working in the reflective mode (once as the incident light impinges on the metasurface, and a second time as it is reflected through and away from the metasurface), thereby allowing for features **2030a**, **2030b**, **2030c** and nanobeams **2020a**, **2020b** with lower heights than a metasurface working in the transmissive mode with similar light redirecting capabilities.

With reference now to FIG. 21B, an example is illustrated of a plot of transmission and reflection as a function of the angle of incidence of light for a metasurface having the general structure shown in FIG. 21A. Various diffraction orders of transmitted and reflected light are indicated by "T" and "R," respectively. In this example, the nanobeams **2020a**, **2020b** are formed of an optically transmissive resist and the features **2030a**, **2030b**, **2030c** are formed of titanium oxide. Titanium oxide has an advantageously high refractive index of 2.6, which can facilitate reductions in the thicknesses or heights of the features **2030a**, **2030b**, **2030c** and nanobeams **2020a**, **2020b** relative to lower refractive index materials. For each unit cell, the width of the nanobeam **2020a** is 50 nm; the width of the nanobeam **2020b** is 110 nm; the gap between the nanobeams **2020a** and **2020b** is 40 nm; the heights of the nanobeams **2020a**, **2020b** are 100 nm; the heights of the features **2030a**, **2030b**, **2030c** are 50 nm; and the pitch of the unit cells **2010** is 382 nm.

With continued reference to FIG. 22B, the percentage of light incident on the metasurface **2008** that is reflected and undergoes first order diffraction to angles suitable for TIR (R_1) is about 25% for an incident angle of 0° , and varies between 25% and 42% for incident angles from about -10° to about 10° . As illustrated, zero order reflection is advantageously low. Where the metasurface **2008** is utilized in a display device such as a display system **250** (FIG. 6) that utilizes a reflective spatial light modulator, zero order reflection may undesirably cause reflection of light back to the spatial light modulator, which then reflects the light back to the viewer, thereby causing undesirable image artifacts such as ghosting. Consequently, a low amount zero order reflection may be desirable in such applications. In addition, as illustrated, a portion of the incident light is transmitted (T_0) and another portion of the incident light undergoes negative first order diffraction (R_{-1}).

With reference now to FIG. 22A, a metasurface **2008** operating in the transmissive mode is illustrated. Notably, in this embodiment, the metasurface **2008** is similar to that shown in FIG. 21A, except for the heights of the features **2030a**, **2030b**, **2030c**, and optionally the material forming these features **2030a**, **2030b**, **2030c**. As illustrated, the heights of the masses **2030c** (and the corresponding heights of the nanobeams **2030a**, **2030b**) may be greater than the heights of the nanobeams **2020a**, **2020b** in some embodiments. In the illustrated embodiment, the light ray **2200** propagates through the metasurface **2008** and is diffracted into an angle such that it propagates through the substrate **2000** by total internal reflection.

With reference now to FIG. 22B, an example is illustrated of a plot of transmission and reflection as a function of the angle of incidence of light for a metasurface having the general structure shown in FIG. 22A. As above, diffraction orders of transmitted and reflected light are indicated by "T"

and “R,” respectively. For each unit cell, the width of the nanobeam **2020a** is 50 nm; the width of the nanobeam **2020b** is 110 nm; the gap between the nanobeams **2020a** and **2020b** is 50 nm; the heights of the nanobeams **2020a**, **2020b** are 150 nm; the heights of the features **2030a**, **2030b**, **2030c** are 190 nm; and the pitch of the unit cells **2010** is 382 nm. In this example, the nanobeams **2020a**, **2020b** are formed of an optically transmissive resist and the features **2030a**, **2030b**, **2030c** are formed of silicon nitride, which has a refractive index of 2.0.

With continued reference to FIG. 22B, the percentage of light incident on the metasurface that is transmitted and undergoes negative first order diffraction to angles suitable for TIR **1**) is about 35% for an incident angle of 0°, and varies between 35% and 56% for incident angles from about -10° to about 10°. Zero order reflection remains advantageously low. As also illustrated, a portion of the incident light is transmitted (To) without being redirected, and another portion of the incident light undergoes positive first order diffraction (Ti).

With reference now to FIGS. 23A-23D, an example of a process flow for forming the metasurface **2008** is illustrated. With reference to FIG. 14A, a layer **2020** of a first material, e.g., resist (such as a nanoimprint resist) is deposited on substrate **2000**. The layer **2020** is preferably optically transmissive and may be deposited by, e.g., spin coating. In some embodiments, the layer **2020** may be deposited by jet coating (e.g., inkjet printing), which may provide advantages for forming exceptionally thin layers, and also layers with varying composition and/or thickness.

With reference to FIG. 23B, an imprint template or master **2024** is brought into contact with the resist layer **2020** to pattern that layer. It will be appreciated that the pattern in the imprint template **2024** may be a negative of the pattern of nanobeams of the metasurface to be formed. The pattern in the imprint template **2024** may be formed by, e.g., lithography, including e-beam lithography or EUV lithography. Advantageously, the same template **2024** may be reused to pattern resist on multiple substrates, thereby reducing per-unit fabrication costs for the eventually-formed metasurfaces.

After contacting the imprint template **2024**, the resist **2020** assumes the pattern defined by the openings in the template **2024**. In some embodiments, the resist **2020** may be cured, e.g., by exposure to light (such as UV light) and/or heat, to immobilize the resist. The template **2024** may then be retracted, to leave a patterned resist having nanobeams **2020a**, **2020b**, as shown in FIG. 23C. In some other embodiments, the pattern in the resist layer may be transferred to an underlying layer of material (e.g., as shown in FIGS. 15A-15E) and the resist may be removed, thereby forming the nanobeams **2020a**, **2020b** in that underlying layer of material.

With reference now to FIG. 23D, a second material is subsequently deposited on the nanobeams **2020a**, **2020b** to form the nanobeams **2030a**, **2030b**. Examples of materials for the second material include semiconductor materials, including silicon-containing materials such as silicon, silicon nitride, silicon carbide; oxides, including zirconium oxide, zinc oxide, and titanium oxide; and optically transmissive resists. As disclosed herein, the second material **2030** is preferably an optically transmissive material. The second material **2030** may be deposited by various processes, including blanket depositions, directional depositions, and spin or jet coating. Examples of blanket depositions include chemical vapor deposition (CVD), in which the resist is exposed to mutually reactive precursors simul-

taneously present in a deposition chamber containing the substrate **2000**, and atomic layer deposition (ALD), in which the resist is alternately exposed to precursors. ALD may provide advantages for precisely controlling the thickness of deposited layers, where high precision is desired, and also for depositing materials at low temperatures. Examples of directional depositions include evaporation and sputtering to deliver the second material preferentially onto the top surfaces of the nanobeams **2020a**, **2020b** and the substrate **2000**.

It will be appreciated that substrates **2000** having metasurfaces according to various embodiments disclosed herein may be used to form display systems, such as the system **1000** (FIG. 6) disclosed herein. For example, the metasurfaces may be utilized as incoupling and/or outcoupling optical elements as noted herein. In some embodiments, after fabrication of the metasurface, the waveguide **2000** may be optically coupled to a light pipe, such as a light pipe for injecting image information into the waveguide. The light pipe may be an optical fiber in some embodiments. Examples of light pipes include the image injection devices **200**, **202**, **204**, **206**, **208** (FIG. 6) and scanning optical fibers. In some embodiments, a plurality of waveguides each having metasurfaces **2010** may be provided, and each of these waveguides may be optically coupled to one or more image injection devices.

Various example embodiments of the invention are described herein. Reference is made to these examples in a non-limiting sense. They are provided to illustrate more broadly applicable aspects of the invention. Various changes may be made to the invention described and equivalents may be substituted without departing from the true spirit and scope of the invention.

For example, while advantageously utilized with AR displays that provide images across multiple depth planes, the augmented reality content disclosed herein may also be displayed by systems that provide images on a single depth plane, and/or with virtual reality displays. In some embodiments where multiplexed image information (e.g. light of different colors) is directed into a waveguide, multiple metasurfaces may be provided on the waveguide, e.g., one metasurface active for each color of light. In some embodiments, the pitch or periodicity, and/or geometric sizes, of the nanobeams, or nanobeams, forming the metasurface may vary across a metasurface. Such a metasurface may be active in redirecting light of different wavelengths, depending upon the geometries and pitches at the locations where that light impinges on the metasurfaces. In some other embodiments, the geometries and pitches of metasurface features are configured to vary such that deflected light rays, even of similar wavelengths, propagate away from the metasurface at different angles. It will also be appreciated that multiple separated metasurfaces may be disposed across a substrate surface, with each of the metasurfaces having the same geometries and pitches in some embodiments, or with at least some of the metasurfaces having different geometries and/or pitches from other metasurfaces in some other embodiments.

Various terms specifying orientation are utilized herein. For example, the nanobeams may be described as being on or over a substrate, and may be described as having a height (or thickness). It will be appreciated that these terms relate to the nanobeams and substrate when placed in a reference orientation in which the substrate is vertically below the nanobeams. In such an orientation, a height describes a vertical dimension, while a gap, pitch, or width describe a lateral dimension, e.g., extending in a plane facing (e.g.,

substantially parallel to) the surface of the substrate on which the nanobeams are disposed. It will be appreciated, however, that the nanobeams and substrates are not limited in their relative orientations and may be positioned in other orientations relative to one another.

Also, while advantageously applied to displays, such as wearable displays, the metasurfaces may be applied to various other devices in which a compact, low-profile light redirecting element is desired. For example, the metal surfaces may be applied to form light redirecting parts of optical plates (e.g., glass plates), optical fibers, microscopes, sensors, watches, cameras, and image projection devices generally.

In addition, many modifications may be made to adapt a particular situation, material, composition of matter, process, process act(s) or step(s) to the objective(s), spirit or scope of the present invention. Further, as will be appreciated by those with skill in the art that each of the individual variations described and illustrated herein has discrete components and features which may be readily separated from or combined with the features of any of the other several embodiments without departing from the scope or spirit of the present inventions. All such modifications are intended to be within the scope of claims associated with this disclosure.

The invention includes methods that may be performed using the subject devices. The methods may comprise the act of providing such a suitable device. Such provision may be performed by the user. In other words, the “providing” act merely requires the user obtain, access, approach, position, set-up, activate, power-up or otherwise act to provide the requisite device in the subject method. Methods recited herein may be carried out in any order of the recited events which is logically possible, as well as in the recited order of events.

Example aspects of the invention, together with details regarding material selection and manufacture have been set forth above. As for other details of the present invention, these may be appreciated in connection with the above-referenced patents and publications as well as generally known or appreciated by those with skill in the art. The same may hold true with respect to method-based aspects of the invention in terms of additional acts as commonly or logically employed.

For ease of description, various words indicating the relative positions of features are used herein. For example, various features may be described as being “on,” “over,” at the “side” of, “higher” or “lower” other features. Other words of relative position may also be used. All such words of relative position assume that the aggregate structure or system formed by the features as a whole is in a certain orientation as a point of reference for description purposes, but it will be appreciated that, in use, the structure may be positioned sideways, flipped, or in any number of other orientations.

In addition, though the invention has been described in reference to several examples optionally incorporating various features, the invention is not to be limited to that which is described or indicated as contemplated with respect to each variation of the invention. Various changes may be made to the invention described and equivalents (whether recited herein or not included for the sake of some brevity) may be substituted without departing from the true spirit and scope of the invention. In addition, where a range of values is provided, it is understood that every intervening value, between the upper and lower limit of that range and any

other stated or intervening value in that stated range, is encompassed within the invention.

Also, it is contemplated that any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein. Reference to a singular item, includes the possibility that there are plural of the same items present. More specifically, as used herein and in claims associated hereto, the singular forms “a,” “an,” “said,” and “the” include plural referents unless the specifically stated otherwise. In other words, use of the articles allow for “at least one” of the subject item in the description above as well as claims associated with this disclosure. It is further noted that such claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as “solely,” “only” and the like in connection with the recitation of claim elements, or use of a “negative” limitation.

Without the use of such exclusive terminology, the term “comprising” in claims associated with this disclosure shall allow for the inclusion of any additional element—irrespective of whether a given number of elements are enumerated in such claims, or the addition of a feature could be regarded as transforming the nature of an element set forth in such claims. Except as specifically defined herein, all technical and scientific terms used herein are to be given as broad a commonly understood meaning as possible while maintaining claim validity.

The breadth of the present invention is not to be limited to the examples provided and/or the subject specification, but rather only by the scope of claim language associated with this disclosure.

We claim:

1. A method for forming a metasurface, the method comprising:
 - providing an optically transmissive substrate;
 - forming a grating comprising a plurality of unit cells across a major surface of the substrate, each unit cell comprising, as seen in a top-down view:
 - a laterally-elongated first nanobeam having a first width; and
 - a laterally-elongated second nanobeam spaced apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width,
 - depositing a layer of optically transmissive spacer material in the gap and between the unit cells; and
 - depositing a reflective layer on the layer of spacer material, wherein the spacer material separates the grating from the reflective layer, wherein the reflective layer comprises a reflective metal material that extends homogeneously and continuously over and across the plurality of unit cells.
2. The method of claim 1, wherein the spacer material has a refractive index of 1 to 2.
3. The method of claim 1, wherein the reflective layer comprises aluminum.
4. The method of claim 1, wherein forming the grating comprises:
 - depositing an optically transmissive layer over the substrate; and
 - patterning the optically transmissive layer to define the grating.
5. The method of claim 4, wherein patterning the optically transmissive layer comprises:
 - providing a resist layer over the optically transmissive layer;

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defining a pattern in the resist layer; and
transferring the pattern from the resist layer to the optically transmissive layer.

6. The method of claim 1, wherein the first nanobeam extends parallel to the second nanobeam.

7. The method of claim 1, wherein the optically transmissive substrate comprises a glass.

8. A method for forming a metasurface, the method comprising:

providing an optically transmissive substrate;

providing an optically transmissive layer over the substrate; and

patterning the optically transmissive layer to define a plurality of repeating units, each repeating unit comprising, as seen in a top-down view:

a laterally-elongated first nanobeam having a first width; and

a laterally-elongated second nanobeam spaced-apart from the first nanobeam by a gap, the second nanobeam having a second width larger than the first width; and

depositing an optically transmissive material on the first and second nanobeams and into the gaps between the nanobeams to form spaced apart masses of the optically transmissive material above the nanobeams.

9. The method of claim 8, wherein the optically transmissive material has a higher refractive index than either the patterned resist or the substrate.

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10. The method of claim 8, wherein patterning the optically transmissive layer comprises patterning resist.

11. The method of claim 10, wherein patterning the resist comprises imprinting the pattern into the resist.

12. The method of claim 10, wherein depositing the optically transmissive material comprises spin coating the optically transmissive material on the patterned resist.

13. The method of claim 10, wherein depositing the optically transmissive material comprises performing a conformal deposition or a directional deposition of the optically transmissive material.

14. The method of claim 13, wherein the conformal deposition comprises chemical vapor deposition or atomic layer deposition of the optically transmissive material.

15. The method of claim 13, wherein the directional deposition comprises evaporation or sputtering the optically transmissive material.

16. The method of claim 8, wherein the first width is 10 nm to 250 nm.

17. The method of claim 16, wherein the second width is 10 nm to 300 nm.

18. The method of claim 8, wherein a pitch of the unit cells is 300 nm to 500 nm.

19. The method of claim 8, wherein the first nanobeam and the second nanobeam are separated by a gap of 10 nm to 300 nm.

20. The method of claim 8, wherein the optically transmissive substrate is a waveguide.

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